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(71) Applicant: FIBER OPTIC NETWORK SYSTEMS CORP. [US/US]; 71 Lyman Street, Northboro, MA 01532 (US).

(72) Inventors: NEMECEK, Joseph, E.; 1 Pointe Rok Drive, Worcester, MA 01604 (US). NOONAN, Michael, J.; 148 South Street, Shrewsbury, MA 01545 (US). MAHAPATRA, Amaresh; 10 Northbriar Road, Acton, MA 01720 (US). ROMANO, Domenic, R.; 11 Rivermeadow Drive, Chelmsford, MA 01824 (US).

(74) Agents: HOOVER, Thomas, O. et al.; Hamilton, Brook, Smith & Reynolds, P.C., Two Militia Drive, Lexington, MA 02173 (US).

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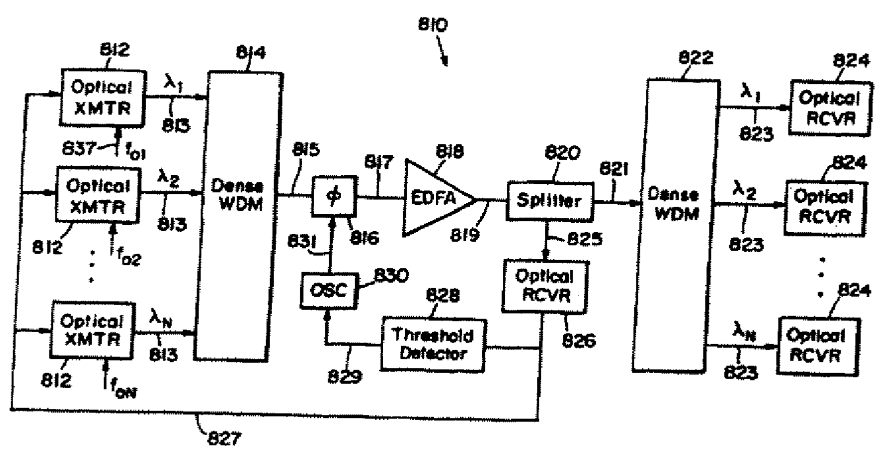

(57) Abstract

A high fidelity, multi-output optical transmission system is configured utilizing a high power continuous wave YAG laser, multiport splitters, and linearized external modulation. An electro-optical modulator design in combination with a continuous wave laser, power splits and couplers attains a multi-octave bandwidth transmitter possessing improved second and third order distortion characteristics. The system includes multiple individually modulated transmitter outputs which effectively provides bandwidth multiplication with full redundancy for increased transmission reliability. An analog lightwave communication system comprises at least two optical transmitters for providing optical information signals at different optical wavelengths. A dense wavelength division multiplexer includes at least two inputs for receiving the optical information signals from the optical transmitters and multiplexes the optical information signals to a composite optical signal at an output. Each input of the dense wavelength division multiplexer comprises at least one optical resonant cavity comprising first and second reflecting materials spaced to permit resonance at a selected wavelength. A fiber optic transmission system coupled to the output of the dense wavelength division multiplexer receives the composite optical signal.

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WAVELENGTH DIVISION MULTIPLEXING SYSTEM

BACKGROUND OF THE INVENTION

The cable television (CATV) industry currently transmits video signals over networks which combine fiber optic transmission and coaxial cable. In the typical network architecture, baseband video signals from a number of sources are combined into specific RF frequencies as amplitude modulated vestigial sideband video subcarriers (AM-VSB) and then modulated onto a laser transmitter located at a headend. The fiber optic transmission systems employed for CATV applications today use internally modulated diode lasers. The internal modulation varies the drive current to the diode laser to produce approximately

10 mW of output power. Typically, the 10 mW output is then optically split into three or four outputs and distributed on fiber into the cable feeder plant to three or four nodes as shown in FIG. 1. Each node converts the optical signal to an electrical signal which is then further distributed over a standard tree and branch coaxial cable network to reach approximately 500 homes per node. This network architecture effectively divides the bandwidth of a single laser transmitter between 1500 to 2000 homes, thus limiting the bandwidth per home.

Increased demand for bandwidth to provide new services such as enhanced pay per view, interactive video, and video on demand requires a larger number of channels per node. A desirable network architecture would include the following characteristics:

- low cost per home
- ability to address target markets
- ability to be configured for two-way interactive video services
- high reliability

A continuing need exists for further improvements in fiber optic transmission systems that will accommodate these various objectives.

Analog lightwave communication systems are typically used in today's CATV trunking and distribution networks. Trunking applications typically are limited to about 40 video channels per fiber due to CSO and CTB considerations. Thus, to carry 80 video channels and maintain transmission quality requires the use of two fibers.

A need exists for an analog lightwave communication system than can transport a greater number of video channels over a single fiber without degrading CSO and CTB performance.

SUMMARY OF THE INVENTION

A fully interactive architecture with the ability to target each individual subscriber may require at least one dedicated video channel per subscriber. One could use a dedicated 2 mW internally modulated laser transmitter, but this would increase the cost per subscriber since the number of internally modulated 2 mW lasers necessary to accommodate larger bandwidths is prohibitively expensive. The present invention provides a linear multi-output optical transmitter system having multi-octave bandwidth multiplication. The solution provided by the present invention allows the full bandwidth to be transmitted so that bandwidth per subscriber is increased. The system takes advantage of optical splitting of a high energy source, external modulation, predistortion, and multi-chip fabrication techniques to provide multiple transmitters having minimized second and third order distortion characteristics for use in fiber optic communication systems such as personal communication networks, telephone systems, computer and/or interactive communication networks and cable television.

The approach to the modulation scheme for the present invention is to minimize distortion over a wide bandwidth while providing multiple transmission systems. To minimize the second and third order distortion products, the invention employs a multi-chip module arrangement comprising dual parallel traveling wave Mach-Zehnder interferometers. The dual parallel Mach-Zehnder modulators are combined with a co-located multi-chip electronic driver circuit having a feed-forward amplifier design which provides pre-distortion shaping to minimize the second and third order distortion residue and enhance performance.

Accordingly, an optical transmission system having reduced second and third order distortion products is provided which includes a continuous wave laser source, having an output power range between about 50 and 500 mW,

and preferably in a range between about 100 and 350 mW, (e.g., a 300 mW YAG laser), for producing an optical carrier signal, an optical splitter coupled to the laser source for splitting the optical carrier signal to a plurality of splitter outputs, and a plurality of transmitters coupled to respective splitter outputs. The high power laser source can also include an optical amplifier to provide an optical output within the desired range above at least 100 mW and preferably over 200 mW. Optical amplifiers operating at either about 1320 nm or about 1550 nm can also be used at remote nodes to amplify the signal over longer distances.

Each transmitter includes a modulator driver, primary and secondary external modulators, and a combiner formed on a single lithium niobate substrate. In the preferred embodiment, the primary and secondary external modulators are Mach-Zehnder modulators. The modulator driver produces primary and secondary driver signals wherein the primary driver signal is scaled and inverted to produce the secondary driver signal. The primary external modulator receives a first portion of the optical carrier signal and modulates the carrier with the primary driver signal to produce a first modulated signal. The secondary external modulator receives a second portion of the optical carrier signal and modulates the carrier with the secondary driver signal to produce a second modulated signal. The combiner superimposes the first modulated signal and the second modulated signal to produce a linearized transmitter output signal.

According to another aspect of the invention, the system further comprises a second continuous wave laser source and an optical switch for switching between the active laser source and the second laser source which can serve as a standby system.

According to a further aspect of the present invention, the modulator driver produces the primary and secondary driver signals according to a predistortion function to compensate for second order products produced by the external modulators.

According to still another aspect of the invention, the system further comprises a ratio detector coupled to the combiner output for detecting second and third order distortion products and for generating correction signals to compensate for such distortion products.

According to yet another aspect of the invention, a transmitter comprising an external modulator and a modulation driver having a distortion network for predistorting a driver signal includes a supervisory signal coupled to a bias input of the modulator. First and second correction circuits coupled to a monitoring optical receiver generate first and second error signals indicative of even and odd distortion respectively in the modulator by monitoring distortion of the supervisory signal. The first error signal is coupled to the modulator bias input to maintain bias about an optical bias point. The second error signal is coupled to a bias processor for adjusting the nonlinear distortion of the distortion network.

According to another aspect, the present invention provides an improved analog lightwave communication system for use in CATV trunking applications to provided increased channel capacity over longer distances without performance degradation.

In accordance with an aspect of the invention, a lightwave communication system comprises at least two optical transmitters for providing optical information signals at different optical wavelengths. A first wavelength division multiplexer includes at least two inputs for receiving the optical information signals from the optical transmitters and multiplexes the optical

information signals to a composite optical signal at an output. Each input of the first wavelength division multiplexer comprises at least one optical resonant cavity comprising first and second reflecting materials spaced to permit resonance at a selected wavelength. A fiber optic transmission system coupled to the output of the first wavelength division multiplexer receives the composite optical signal.

A preferred embodiment of the system uses at least two, and preferably 3 or 4 sources, each operating at different wavelengths in the range of 1530 nm to 1565 nm. The sources can include a temperature control feedback circuit to maintain the output of each laser at a wavelength corresponding to one of the fixed wavelengths of the multiplexer.

According to another aspect of the present invention, each optical transmitter includes a DFB laser source which provides a continuous wave optical signal and an external modulator coupled to the laser source. An RF driver coupled to an RF electrical input of the external modulator provides an RF information signal for modulating the continuous wave optical signal to produce the optical information signal.

According to another aspect of the invention, an oscillator circuit providing a single tone modulation signal for driving a phase modulator having an optical input coupled to the output of the first wavelength division multiplexer. The single tone modulation signal drives the phase modulator to modulate the composite optical signal such that stimulated Brillouin scattering threshold in the system is increased.

According to another aspect of the invention, an optical monitoring receiver coupled to the output of the first wavelength division multiplexer receives a portion of

the composite optical signal and controls the level of the single tone modulation signal.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views.

FIG. 1 is a representation of a prior art CATV distribution arrangement.

FIG. 2A is a schematic block diagram of a preferred embodiment of the present invention.

FIG. 2B is a block diagram of an unequal power splitter arrangement for use in the system of FIG. 2A.

FIG. 2C is a block diagram of a variable power splitter arrangement wherein liquid crystal polarizers are used.

FIG. 3 is a block diagram of the external modulation block of the system in FIG. 2A.

FIGs. 4a-4c are graphs schematically illustrating the distortion cancellation achieved by the external modulation block in FIG. 3.

FIG. 5 is a graph schematically illustrating the transfer function of an external modulator.

FIG. 6 is a block diagram of the RF modulator driver block of the system in FIG. 2A.

FIG. 7 is a schematic block diagram of an RF modulator driver circuit of the modulator driver block in FIG. 6.

FIG. 8 illustrates a network topology employing the present invention.

FIG. 9 illustrates the use of the invention in a personal communication network.

FIG. 10 is a process flow sequence for manufacturing a multi-chip module in accordance with the invention.

FIG. 11 illustrates the sections of the external modulation block of FIG. 3.

FIG. 12 is a block diagram of an alternate RF modulator driver for the system of FIG. 2A.

FIG. 13 is a schematic block diagram of another preferred embodiment of the present invention.

FIG. 14 is a schematic circuit diagram of a parallel diode configuration for use as the distortion network of FIG. 13.

FIG. 15 illustrates a configuration of a multi-chip diode layout for use in the distortion network of FIG. 13.

FIG. 16 is a schematic block diagram of an automatic bias control circuit for use in the embodiment of FIG. 13.

FIG. 17a is a top view of a rack mountable module embodying the present invention.

FIG. 17b is a side view of the module of FIG. 17a.

FIG. 18 is a front view of a system configuration embodying the present invention.

FIG. 19 illustrates the use of the invention in a CATV network for upstream transmission.

FIG. 20A is a block diagram of an embodiment wherein multiple wavelengths provided by a multimode laser source are separately modulated.

FIG. 20B is a block diagram of an embodiment which provides improved optical cancellation with line spreading.

FIG. 21 is a schematic block diagram of an optical communication system in accordance with the present invention.

FIG. 22 is a schematic block diagram of an optical transmitter for use in the system of FIG. 21.

FIG. 23 is a schematic diagram of a dense wavelength division multiplexer for use in the system of FIG. 21.

FIG. 24 schematically illustrates a resonant cavity filter arrangement for the dense wavelength division multiplexer of FIG. 23.

FIG. 25 is a schematic diagram of an oscillator circuit for providing single tone phase modulation in the system of FIG. 21.

FIG. 26 is a schematic diagram of an automatic bias control circuit for use in the system of FIG. 21.

FIG. 27 is a schematic diagram illustrating another preferred embodiment of a dense wavelength division multiplexer.

FIG. 28 is a schematic diagram illustrating an optical guide portion of the dense WDM of FIG. 27.

FIG. 29 is a schematic diagram illustrating a configuration for WDM and power splitter.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a linear multi-output optical transmitter system having multi-octave bandwidth multiplication. The system takes advantage of optical splitting, external modulation, predistortion, and multi-chip fabrication techniques to provide multiple transmitters having minimized second and third order distortion characteristics.

Referring to FIG. 2A, a preferred embodiment of the present invention is shown. A continuous wave (cw) laser source 12 is coupled through an optical switch 16 to an input 17 of an optical divider splitter 18. The optical splitter 18 is a 1 x N polarization maintaining planar optical waveguide, configured in the preferred embodiment to provide N=32 individual outputs. In other embodiments, N = 16 or another number depending on the particular application. For N = 32, the 1 through 32 outputs 20a-20n are coupled to individually modulated transmitters 22a-22n. The transmitters 22a-22n provide dual outputs 32a, 34a

through 32n, 34n for a total of 32 dual channels or 64 individual outputs. Thus, the system 10 can split and modulate an optical carrier signal S1 of the single cw laser source 12 to serve up to 64 downstream receiver nodes.

A standby cw laser source 14 is optically coupled to the optical switch 16 to provide a standby laser source for the system. Each of the cw laser sources 12 and 14 is preferably a 300 mW yttrium aluminum garnet (YAG) laser. The optical signal on line 15 is monitored by a photo detector 37 coupled through line 36. In the event the power from the active laser source 12 falls below a minimum threshold level, the optical switch 16 will be activated via an enable signal 39 to switch the standby laser source 14 into service on line 15.

The transmitter 22a includes an external modulation block 24a, an RF modulator driver block 30a, and a ratio detector 35a, each of which is described further below. The external modulation block 24a includes dual external modulators 26a, 28a in a parallel configuration. The external modulators 26a, 28a are driven in parallel by the RF modulator driver block 30a. The ratio detector 35a detects distortion products and produces correction signals in response thereto which are input to the RF modulator driver block 30a.

The optical splitter 18 provides an equal power split among the N individual outputs 20a-20n. A CATV network architecture can have different path loss budgets across the individual transmission paths leading to the network nodes. The system of the present invention can be configured to provide a range of unequal power outputs. In one embodiment, the optical splitter 18 is replaced with an unequal power splitter 18' shown in FIG. 2B.

The splitter 18' can have a combination of different percentage split ratios for coupling larger or smaller

percentages of optical power from laser source 12 to the transmitters 22a-22n. For example, splitter output 20a' can receive 5% of the optical power, output 20b' can receive 10%, and output 20n' can receive 20% of the output power. The remaining outputs can receive power according to still different percentage split ratios. These percentages are given by example and in no way are meant to limit the invention.

In another approach, an electronic power controller is used to provide variable power to multiple transmitters. The electronic power controller can be a twisted nematic liquid crystal polarizer which includes a bias control for varying the polarization in combination with a prism. FIG. 2C shows a system of the present invention having a variable splitter arrangement 18" which includes liquid crystal polarizers 21a-21n coupled to the output 17 of laser source 12. The liquid crystal polarizers include bias controls 19a-19n which can be coupled to a microcontroller to control the power split to transmitters 22 coupled to the output. With this arrangement, the polarizer split ratios can be remotely programmed to values which provide the required power for a given network distribution layout. The twisted nematic liquid crystal polarizers 21a-21n can be, for example, of the type disclosed in U.S. Patent No. 4,917,452, the contents of which are incorporated herein by reference.

Referring to FIG. 3, the external modulation block 24a is shown in more detail. An optical carrier signal on output path 20a from optical splitter 18 (FIG. 2A) is coupled to a proportional coupler 64 which splits the optical signal proportionally onto paths 66 and 68 such that path 66 carries 80% of the signal and path 68 receives 20%. The proportional outputs on paths 66, 68 are respectively coupled to inputs 63, 65 of the dual external modulators 26a, 28a.

The dual external modulators 26a, 28a are preferably Mach-Zehnder interferometers. External modulator 26a has an individual control portion which includes a center electrode 54 and outer electrodes 52, 56. Dual waveguides 72 of external modulator 26a extend in the spaces between the electrodes. External modulator 28a is similarly configured with center electrode 60, outer electrodes 58, 62 and dual waveguides 74. The outer electrodes 52, 56, 58, 62 of the external modulators are connected to ground potential. The center electrode 54 of external modulator 26a is connected to a main driver signal from RF modulator driver block 30a (FIG. 2A). The center electrode 60 of external modulator 28a is connected to a scaled and inverted driver signal from RF modulator driver block 30a (FIG. 2A). The modulated outputs 67, 69 of the respective Mach-Zehnder modulators 26a, 28a are superimposed at a combiner 70 to produce resultant dual outputs 32a, 34a.

Prior work on external modulation has been focused on single octave bandwidth and special applications at a single frequency. Recently there has been work on using dual modulators focused on noise figure in a sub-octave bandwidth, series modulator configuration, where second order distortion is not a problem and signal to noise improvement is addressed.

The approach of dual parallel modulation is described in Korotky et al., "Dual Parallel Modulation Schemes for Low-Distortion Analog Optical Transmission", IEEE Journal on Selected Areas in Communications, Vol. 8, No. 7, September 1990. Dual parallel modulation achieves linearization by using the distortion created by a secondary modulator to cancel the distortion produced by a primary modulator. The present invention improves upon the known dual parallel linearization schemes by providing coherent dual parallel linearization without requiring additional phase modulation in either of the two modulator

output paths to maintain quadrature between the primary and secondary modulator signals.

In the preferred embodiment, external modulators 26a, 28a function respectively as the primary and secondary modulators to achieve cancellation of the third order components in the modulated optical signal produced on the outputs 32a, 34a as shown in FIG.s 4a-4c. Although the fundamental suffers a small loss of power, this is a practical implementation. The need for additional phase modulation in either of the two modulator output paths to maintain quadrature between the primary and secondary modulator signals is eliminated in the scheme of the present invention by the processing technique utilized to fabricate a single lithium niobate die having very controlled photolithographic processes and diffusion. The process of annealing this multi-chip die at low temperatures in a wet oxygen bath subsequent to an initial titanium diffusion phase stabilizes the device. This stabilization process in effect eliminates any changes in phase in an operational environment.

An external modulator has a sinusoidal transfer function which results in second and third order distortion products in the modulated output signal. The transfer function is illustrated in FIG. 5. Operating such a modulator at a quadrature point, i.e., a DC bias of $\pi/2$, eliminates even-order distortion products. However, in reality, a perfectly symmetrical sine function cannot be achieved. The lack of sine wave symmetry creates second order residue over the operational bandwidth.

The Mach-Zehnder modulators 26a, 28a are each operated at the quadrature point $\pi/2$. Maintaining the modulators 26a, 28a at their respective quadrature points is achieved by the ratio detector 35a in combination with the RF modulator driver block 30a (FIG. 2A). The ratio detector 35a monitors second and third order distortion and creates

feedback correction signals to the modulator driver block 30a which in turn repositions the DC bias on the modulation curve, as discussed further below. The ratio detector 35a couples a small portion (e.g., 5%) of the output signal 34a to an optical receiver. The signal detected by the optical receiver is used to generate the feedback correction signals.

The theory of the ratio detector 35a can be understood by first noting that the optical field signal input to the external modulation block 24a varies as:

$$E_{in}=A \cos\omega t$$

$$E_{out}=A \cos\left[\omega t - \frac{\omega}{c}\left(n_o - \frac{n_o 3}{2}\, r\, E_m \sin\omega_m t\right) l\right]$$

where l is the optical path length through the lithium niobate crystal.

Rewrite as

$$E_{out}=A \cos[\omega t + \delta \sin\omega_m t]$$

where δ is the phase modulation index, and

$$\delta = \frac{\omega n_o^3\, r\, E_m\, l}{2c} = \frac{\pi\, n_o^3\, r\, E_m\, l}{\lambda}$$

using Bessel function identities:

$$\cos(\delta \sin\omega_m t) = J_o(\delta) + 2J_2(\delta)\cos\omega_m t \ldots$$

$$\sin(\delta \sin \omega_m t) = 2J_1(\delta) \sin \omega_m t + 2J_3(\delta) \sin 3 \omega_m t$$

Rewriting:

$$E_{out} = A\,[J_o(\delta) \cos\omega t + J_1(\delta) \cos(\omega + \omega_m)\, t$$

$$- J_1(\delta) \cos(\omega - \omega_m)\, t + J_2(\delta) \cos(\omega + 2\,\omega_m)\, t]$$

Detecting the ratio of J_2/J_1 and producing a feedback correction signal can compensate for any second order distortion. Additionally, the ratio of J_3/J_1 can be used to produce a correction signal to keep the DC bias at $\pi/2$.

Typical industry standards require that total distortion products in an operational CATV distribution system be maintained below -60 db over the entire bandwidth to meet the fidelity expected by individual subscribers. Factors which limit amplitude modulation over multi-octave bandwidths are noise figure, dynamic range and bandwidth of driver electronics. Since an external optical modulator has a very large modulation bandwidth, multi-chip RF modulator drive circuitry is employed to meet performance over multi-octave bandwidth, as shown in FIG. 6. In order to cover the wide bandwidth possible with the multi-chip modulation scheme, individual RF modulator driver circuits 100 are coupled to a passive broadband equalizer combiner 102. The equalizer combiner 102 in turn drives the optical modulators from a single output 31a. In the preferred embodiment, the individual RF modulator driver circuits 100 are divided into four bands: 5 MHz to 1 GHz, 1 GHz to 2.5 GHz, 2.5 GHz to 5 GHz, and 5 GHz to 10 GHz. These bands are noted for example purposes only and not as a limitation on the present invention. The equalizer combiner 102 comprises a configuration of low pass filters 104 in series and high pass filters 106 in parallel.

FIG. 7 shows an RF modulator drive circuit 100 of the RF modulator driver block 30a. The RF modulator drive circuit 100 uses feed forward cancellation. Feed forward cancellation inverts a sample of the undistorted input signal and adds it to a signal of a main line amplifier output containing both the input signal and distortion products created within the main line amplifier itself. The resultant output includes the distortion products which are inverted and amplified by a highly linear distortion amplifier A4 and then linearly summed with a main line amplifier output signal combining vectorally to cancel the distortion products.

Referring to FIG. 7 to provide more details of the RF modulator driver circuit 100, a baseband input signal 105 is level set using input attenuator R1. The level to input signal 105 is provided from an external source from a down converted signal. The attenuator R1 assures that any input level is below a point where internal amplifiers can approach a saturation level which generates internal distortion. The input signal 105 is amplified through amplifiers A1, A2 and MAIN LINE amplifier A3 to produce output signals 108a, 108b which are 180 degrees out of phase relative to each other. The output signals 108a, 108b provide the RF input which modulates the optical carrier signal in the external modulation block 24a (FIG. 2A).

Distortion in the RF driver signal is detected by the distortion detector diode D1. A distortion signal is coupled through coupler X1 to the MAIN LINE amplifier A3 with any distortion component 180 degrees out of phase with the signal simultaneously coupled through coupler X1 on the AUX LINE due to voltage variable phase shifter PS. A portion of the signal which has distortion in the MAIN LINE is coupled back through couplers X2, X3 at 180 degrees out of phase and added to the AUX LINE signal. This combined

signal is amplified by distortion amplifier A4 and coupled through couplers X5, X4 to the MAIN LINE signal at a 180 degrees phase shift.

Additionally, a tone source 110 is coupled to the RF driver circuit through MAIN LINE amplifier A3 to provide a tone signal for the purpose of detecting distortion in the external modulation block 24a through ratio detector 35a (FIG.s 2A and 3). The tone signal, preferably at a frequency outside the operational bandwidth, e.g., below 50 MHz, is proportional to the RF drive and can generate distortion side bands as described below. An output 38aa from the ratio detector 35a (FIG. 2A) is input to amplifier A2 to correct for any second order distortion. An output 38ab from the ratio detector 35a is input to amplifier A5 to correct the DC bias to the external modulation block 24a such that the quadrature point is maintained. The output of amplifier A5 passes through a lowpass filter F1 and feeds a voltage-variable attenuator R2.

The operational amplifiers A5 and A6 form a summing junction for an AGC correction loop. This junction sums an error feed back from the amplifier and optical modulation. The AGC loop which is a second order loop is established through amplifiers A5 and A6 and closed through the phase shifter PS and attenuator R2. The filters F1 and F2 set the loop time constraints establishing noise rejection and time bandwidth products for loop response. The distortion correction and DC bias is maintained through the AGC loop. The DC bias to the amplifier is buffered and scaled through amplifier A7 and fed to the optical modulator to maintain a $\pi/2$ bias condition on the modulation curve.

The linear multi-output optical transmitter system of the present invention allows a greater number of transmitters to be driven from one high powered laser. Referring to FIG. 8, a layout is illustrated in which the system 10 of the present invention is located at a headend

site 200. Each individual modulated transmitter is shown supporting a single node 202 with redundant outputs 32a, 34a over optical fibers 201, 203 respectively. In addition, the nodes 202 can be connected through a daisy chain 204 to provide further redundancy. This redundant configuration increases both network reliability and subscriber bandwidth. Alternatively, the redundant outputs 32a, 34a can each support a single node, thereby increasing the number of subscribers served. In the preferred embodiment, either 32 redundant nodes or 64 individual nodes can thus be supported. With either configuration employing the present invention, service providers can distribute more services over the same cable plant with a transmitter cost that is far less than today's cost.

It is important to note that the scope of the present invention includes embodiments in which the RF modulation can be one of several digital modulation techniques suitable for digital TV transmissions, for example, double sideband quadrature amplitude modulation (QAM) and multi-amplitude vestigial sideband (VSB) modulation. Such digital modulation can be accommodated in the preferred embodiment of FIG. 2A by substituting suitable digital external modulators for the Mach-Zehnder modulators 26a, 28a described herein.

In addition to present communication networks, the transmitter system of the present invention is well-suited to address emerging personal communication networks (PCNs). PCNs are wireless networks which are being configured to operate at 2 and 4 GHz. One method favored for PCN transmission uses a spread spectrum technique whereby a very low power RF signal having a wide frequency range is transmitted. There are significant drawbacks to operating with this scheme. First, the higher carrier frequency (e.g. 2 GHz) cannot penetrate obstructions but is instead

absorbed. Thus, PCN transmission is line of sight. Second, spread spectrum requires a wide bandwidth.

The relatively large bandwidth and high frequencies of PCNs are well-suited to the present invention. Referring to FIG. 9, a layout is schematically illustrated in which the system 10 of the present invention is located at a cell site 300. An obstruction 308, e.g., a building, separates cell site 300 from another cell site 320. The multi-octave bandwidth capability of the electronic driver and optical modulator of the system 10 allows direct modulation by an RF input signal from an RF receiver 310. The output from the system 10 can be transported through or around the line of sight obstruction 308 via an optical fiber cable 312 to be received and retransmitted at cell site 320. The signal is received by an optical receiver 314 and retransmitted by RF transmitter 316. An advantage of the present invention in this arrangement is that down conversion and up conversion of the RF signal at the respective cell sites 300, 320 is eliminated.

A significant feature of the transmitter system is its modular packaging. The modularized configuration allows for individual testing of components and ease of access and replacement which enables the system to meet the performance and size constraints required by industry in an operational environment. Specifically, each driver and modulator can be mounted on a common module body. Thus in the preferred embodiment, the total transmitter assembly comprises 32 dual or 64 single transmitters packaged in an area two orders of magnitude smaller than equivalent transmitters existing today. For example, the transmitter assembly can fit in a 14 inch panel while an equivalent transmission system with existing technologies occupies three full 84 inch racks.

As noted above, the transmitter module includes a multi-chip electronic driver and a dual parallel multi-chip

modulator. The dual parallel multi-chip modulators can be fabricated on a single substrate of lithium niobate which insures control of the basic phase and propagation delay parameters. Referring again to FIG. 3, the external modulation block 24a is fabricated on a common lithium niobate substrate to form a multi-chip configuration. The dual chip is packaged in either a Kovar or ceramic package having co-efficient of expansion characteristics which are small over the entire environmental range. Line length and width can be controlled to maintain both phase and amplitude which are critical to performance. The Mach-Zehnder modulators 26a and 28a are traveling wave interferometers which offer the advantage of allowing a lower drive voltage, e.g., approximately +/- 1.5 volts into 50 ohms. This in turn reduces the burden on the RF modulator driver circuitry discussed above. The optical modulator and the optical dividers employ similar processing techniques - vapor phase deposition, molecular beam epitaxy, diffusion, and bath metal dry etch. A completed package may include a planar waveguide divider, modulator, and electronic driver configured in an electro-optic multi-chip module.

The driver is formed in a chip mounted on a common teflon glass substrate as a low dielectric carrier. This configuration eliminates differential propagation delay and matches the input and output impedance to the modulators. The multi-chip technique uses unpackaged integrated circuits mounted on a substrate and interconnected by conductors applied using a deposition and photolithography process. The input modulation bandwidth of the lithium niobate optical modulator can be 10 GHz or higher. Providing the RF electrical drive to this device requires traversing several technologies. The low end band requires silicon devices and a teflon glass substrate. Gallium arsenide devices and micro strip transmission lines are

used in the higher end. Therefore, one of the keys to achieving performance over the range of frequencies between 5 MHz and 10 GHz is a modularized multi-chip configuration for each range. Another key ingredient is that path length and differential propagation delay are minimized by employing an "embedded chip on carrier" approach. The embedded multi-chip design uses a photolithography process to create exact line width and length which also provides matching structures. The coupler and delay lines in the lower bandwidth configuration made with active silicon components are formed of a lump constant and a low dielectric teflon glass substrate implemented as the carrier.

FIG. 10 illustrates a process of fabricating a multi-chip module in accordance with the invention. In this particular application, both high 350 and low 352 frequency drivers are separately fabricated on gallium arsenide and silicon wafers respectively. The modulator elements 354 are also separately fabricated and all these elements are mounted on a common module body at 356. Both optical and electrical interconnects are then formed between module elements using selected line width and length parameters to provide improved operational characteristics.

As described herein, the external modulation block 24a of the preferred embodiment shown in FIG. 3 comprises a proportional coupler 64, dual external modulators 26a, 28a and combiner 70 fabricated on a single substrate. To achieve effective linearization using the dual parallel modulation cancellation technique requires precise splitting ratios in the proportional coupler 64 and the combiner 70. A method has been discovered for optimizing these splitting ratios. Initially, the external modulation block 24a is fabricated on a single substrate as shown in FIG. 11. The device is then cut along lines X-X and Y-Y respectively. Line X-X divides the output of coupler 64

and the input to modulators 26a, 28a. Line Y-Y divides the output of modulators 26a, 28a and the input of combiner 70. After cutting the device along these lines, the resulting coupler sections 64', 70' are polished. The coupler sections 64', 70' can then be tested individually, with fine tuning by additional post baking or diffusion as needed to achieve the optimal splitting ratio. The optimized coupler sections 64', 70' are then aligned and reattached to the central modulator section. Note that since the coupler sections were cut from the same original device, the waveguides can be substantially aligned.

Note that for an external modulator the bandwidth and the modulation efficiency as measured by Vπ are inversely related. Therefore, the modulator design should be optimized for the bandwidth of interest. For instance, modulators with bandwidth of 30 Ghz (3 dB electrical bandwidth) with Vπ of 5.0 volts have already been demonstrated. (see for example, 75-Ghz Ti: LiNbO3 optical modulator," K. Noguchi et al., OFC '94 Technical Digest, Paper no. WB3. page 76). Therefore, we have designed a modulator with a bandwidth of 1 GHz for a CATV system with a Vπ of 1 volt. This will result in considerable reduction in RF power and cost of drive electronics. To optimize performance of the system over large bandwidth, the following alternative to the driver of FIG. 6 can also be implemented as shown in FIG. 12.

In the arrangement shown in FIG. 12, RF modulator driver circuits 370 are coupled to respective optical modulators 372. Instead of combining the RF driver circuit outputs to drive a single modulator as in the first embodiment, in this arrangement the RF drivers 370 individually drive bandwidth optimized modulators 372. The output of the modulators 372 is then combined through optical combiner 376.

Referring to FIGs. 13-16, an alternate embodiment of the invention will now be described. The goal of the preferred embodiments, as noted earlier, is to minimize second and third order distortion products over a wide bandwidth.

The alternate embodiment illustrated in FIG. 13 provides a system 400 comprising a single external optical modulator 422 driven by an electronic driver 402, both of which are bias controlled by an automatic bias control circuit 428. The electronic driver 402 includes a distortion network 418 which performs a predistortion function on the RF input to compensate for third order distortion generated by the modulator 422. A continuous wave (cw) laser source 420 is coupled to the modulator 422, which is preferably a Mach-Zehnder modulator.

The automatic bias control circuit 428 monitors the optical output signal from the modulator 422 and generates bias correction signals to control the distortion network 418 and to maintain the modulator 422 at the quadrature point. The automatic bias control circuit 428 injects a supervisory tone signal on the DC bias electrode 429 of the modulator 422. The frequency of the supervisory tone signal is selected to be below the lower limit of the CATV RF bandwidth, i.e., below 50 MHz.

Referring to FIG. 13, the operation of driver 402 will now be described. An RF input signal is coupled to main amplifier 406. A portion of the output of main amplifier 406 is coupled through a feedback detection circuit comprising RF detector 412 and feedback amplifier 413 which provides a feedback signal to gain control 403 to maintain the RF driver signal 411 at a constant amplitude over the entire RF bandwidth. A sample signal 405 of the RF input signal is applied to a distortion network 418 through attenuator 414 and error amplifier 416. The distortion network 418, described further below, generates odd-order

distortion products in signal 419 which compensate for nonlinearities generated by modulator 422. These distortion products are then recombined with the output 407 of the main amplifier 406 by coupler 408 to create a composite signal 411 to drive the modulator 422. The nonlinear modulation of the modulator 422 effectively generates odd-order distortion products of opposite phase to that of the applied composite signal 411. Since the amplitude of the odd-order products generated by the modulator 422 match the amplitude of the distortion products in signal 419, the odd-order distortion of the modulator 422 is effectively cancelled.

A loading detector 478 samples a portion of the RF input signal to provide a measure of the channel loading present in the RF input signal. The loading detector 478 employs active filtering to perform frequency discrimination which is indicative of channel load. A loading detector output signal 479 is coupled to bias processor 476 which processes the signal to yield a coarse bias optimization for the distortion network 418. A fine bias optimization is determined by the bias processor 476 based on a bias optimization signal 473 received from automatic bias control circuit 428 described further herein.

The bias processor 476 can be a single chip micro processor such as a HD6802 MPU manufactured by Hitachi. The bias processor 476 has look up tables (LUTs) stored in memory. The processor accesses the bias LUT based on the channel loading and presets the distortion network 418. The fine bias adjust can be programmed based on the optical receiver sampling of the odd order distortion providing an iterative process either in a Monte Carlo or least square process to minimize the distortion with adjustment of the bias on the individual diode. The bias processor can also

be used in the event of any asymmetry to fine tune the modulator quadrature point.

Referring to FIG. 14, a parallel diode configuration for use in the distortion network 418 is shown. It has been recognized that an inverse sine function which compensates for the nonlinearity of the modulator 422 can be approximated from a diode. The diode configuration of FIG. 13 is a preferred arrangement. The distortion network 418 comprises a first series of diodes 430 coupled in anti-parallel fashion to a second series of diodes 432. The diode series 430, 432 are forward biased through voltage sources V- and V+ respectively. Though twelve diodes are shown in each diode series, the actual number of diodes is likely to range from 2 to 12 diodes, depending upon the size of the desired V_o, where V_o is the amplitude of distortion products in distortion network 418 and is proportional to channel loading and the modulation index.

The treatment for utilizing diodes to generate non-linear products was reported in "Theory of Nonlinear Distortion Produced in a Semiconductor Diode", K. V. Lotsch, IEEE Transactions on Electron Devices, May, 1968. Lotsch's treatment define the small signal approximations and provides universal curves for these distortions. To provide an implementation, one must take into account the amount of distortion correction required. Therefore, general aspects must be considered: 1) providing extremely low group delay in the circuit; 2) minimizing the amplitude to phase conversion (AM to PM); 3) compensating for the effects of channel loading and modulation index versus amplitude of distortion.

The group delay and AM to PM conversion have been addressed by the packaging techniques utilized by the diode layout to minimize reactive components. The effects of channel loading are handled by the number of diodes. The key is to generate the distortion amplitude required by the

channel loading while matching the small signal characteristics of each diode. This is resolved by the number of diodes and the biasing technique using a bias processor to set the level as needed for each diode. To minimize parasitics, diode arrays such as the HSMS-2812 Schottky Series Diode devices manufactured by Hewlett Packard are preferred as shown in the multi-chip diode configuration of FIG. 15. In this configuration, a first series of six diode devices 430' are coupled in anti-parallel fashion to a second series of diodes 432'. Input electrode 431 and output electrodes 433 are metal striplines fabricated on an alumina substrate.

Referring to FIG. 16, the automatic bias control circuit 428 is illustrated. The supervisory tone signal 447 is generated by a 24 MHz oscillator 440, the output of which is divided down by divider 442 to a 2 MHz carrier signal f_o and to 4 and 6 MHz reference signals $2f_o$, $3f_o$ respectively. A 1 KHz square wave signal produced by square wave generator 452 modulates the 2 MHz carrier signal in AM modulator 444 and the modulated output is filtered by bandpass filter 446 to yield the supervisory tone signal 447. As noted earlier, the supervisory tone signal 447 is injected on the DC bias input of the external optical modulator 422 (FIG. 13). It has been found that injecting the supervisory tone signal 447 on the DC bias input instead of mixing the signal with the RF input 411 (FIG. 13) provides better isolation and thus reduces unwanted intermodulation products generated by cross modulation between the two signals.

The predistortion linearization technique utilizes a non-linear device which generates distortion products that are equal in amplitude and opposite in phase of the non-linear products generated by the optical modulator. The complementary distortion products in the CATV application are dependent on the optical modulation index and channel

loading. The modulation index is a percentage of modulation on the carrier and is proportional to the scale factored drive voltage on the optical modulator. The voltage traverses an angular portion of the non-linear sine curve, i.e., the greater the loading the greater the angle subtended on the curve. Monitoring the channel loading and adjusting the bias to the predistortion network with the bias processor 476 optimizes the day-to-day and installation-to-installation handling.

A monitor signal 461 containing distortion products generated by the modulator 422 is output from optical receiver 426 (FIG. 13) and split by RF splitter 462 to form inputs to even-order correction circuit 463 and odd-order correction circuit 465 both of which correct intermodulation distortion on the basis of quadrature detection of the distorted supervisory pilot signal 447. The correction circuits 463, 465 do not use the out of phase control suggested by other bias control schemes.

The correction circuits 463, 465 comprise identical elements, differing only on the passband of interest. The operation of the even-order correction circuit 463 will now be described further. A portion of the monitor signal is filtered through bandpass filter 464 around the passband containing second order distortion products, which for a supervisory tone signal at 2 MHz would be a passband centered around 4 MHz. For the odd-order correction circuit 465, the passband is centered around 6 MHz.

The filtered monitor signal is fed through preamp 468 to a phase lock tone demodulator 456 which in conjunction with phase shifter 454 performs a phase lock loop detection function on the monitor signal to produce a quad error signal 457. The quad error signal 457 is input to digital correction logic 474 to produce bias control signal 475 which is input to the DC bias input of the modulator 422.

Odd-order correction circuit 465 includes a phase lock tone demodulator 460 which produces a quad error signal 459. The error signal 459 is input to digital correction logic 472 to yield third order bias optimization signal 473 which is coupled to bias processor 476 (FIG. 13) for adjusting fine bias of the distortion network 418.

The quadrature phase lock loop of correction circuit 463 senses and maintains the bias applied to the DC bias input of the optical modulator 422 for minimizing second order products. The quadrature phase lock loop of correction circuit 465 senses and maintains the bias to the distortion network 418. The dynamic bias control provides for adjustment of the distortion network 418 as the information bandwidth expands. For example, consider an application of the alternate embodiment 400 in a CATV system, in which a CATV provider initially operates over a bandwidth from 50 MHz to 450 MHz with 60 analog channels. An expansion to a bandwidth of, for example, 50 MHz to 1 GHz generates a different set of distortion products in the modulator 422. The dynamic bias control provided by the automatic bias control circuit 428 in conjunction with bias processor 476 (FIG. 13) automatically adjusts the bias of the distortion network 418 to linearize the RF input signal over the bandwidth.

In a preferred mode of operation, the quadrature point of the modulator 422 is maintained at $V\pi/2$ such that the linear region of the modulator transfer function has a positive slope as shown in FIG. 5.

The RF match of the optical modulator 422 is flat both in amplitude and phase with a return loss of -20dB allowing for broadband operation with minimal group delay.

It should be noted that the alternate embodiment of FIG. 13 can be used with components of other embodiments, e.g., the driver/modulator configuration of FIG. 13 can be substituted for the transmitter 22a in FIG. 2A.

Referring to FIGs. 17a, 17b and 18, a system configuration embodying the present invention will now be described. A rack mountable module 500 is illustrated in the side and front views of FIGs. 17a and 17b respectively. The module 500 includes an external optical modulator subassembly 501 and an electronic driver package 504. The optical modulator subassembly 501 incorporates a modulator 502 of the type disclosed in the other embodiments of the invention and further includes an optical receiver 506. Similarly, the driver package 504 incorporates an electronic driver of the type described in the other embodiments. The modulator 502 includes optical input and output ports 505, 507 respectively and driver electrodes 503. The driver package 504 and the modulator subassembly 501 are both mounted to a common plate 511. A faceplate 510 mounted to the module includes a handle 512 to facilitate rack mounting of the module in a system configuration as shown in FIG. 18.

The system configuration of FIG. 18 further incorporates components of the present invention including dual laser sources 514, dual laser power supplies 518, splitter 516, and eight modulator/driver modules 500 configured to mount to a 14 inch x 26 inch mounting panel or housing 520. As described above in relation to the other embodiments, in this configuration, laser source 514 is a cw YAG laser which is split by 8:1 splitter 516. An individual output of splitter 516 is coupled to each modulator/driver module 500. The configuration of FIG. 18 illustrates the high density packaging possible with the present invention.

The transmitter system of the present invention is well-suited to address remote modulator configurations for use in emerging CATV architectures. FIG. 19 illustrates a remote modulator configuration, also referred to as "echo

back", which provides upstream transmission capability for such services as telephony, internet access and video.

At a fiber node 600, a fiber optic cable 614 transmitting a downstream signal 616 from a remote transmitter is coupled to a conventional optical receiver 606 which produces an RF output. A portion 618 of the downstream signal 616 is split by splitter 604 and coupled to the optical input of external optical modulator 610. A depolarizer 608 coupled between the splitter 604 and modulator 610 depolarizes the signal 618 to enhance the modulation operation of modulator 610. A driver 612 drives the modulator 610 with an RF driver signal 620 based on an RF input at the node 600. The output of modulator 610 is then coupled to fiber optic cable 614 through coupler 602 for upstream transmission of the modulated carrier signal 622. Alternatively, the output of modulator 610 can be coupled to a separate upstream fiber optic cable. The upstream transmission for the configuration of FIG. 19 uses a 5 MHz - 40 MHz passband. Other passbands can be used including a passband above the downstream passband.

In fiber optical communication applications such as described above for CATV, telephony, cellular, and PCS, suppression of Stimulated Brillouin Scattering (SBS) is desirable. A solid state laser capable of operating with several longitudinal modes to suppress SBS is disclosed in U.S. Patent No. 5,461,637, the entire contents of which are incorporated herein by reference. Such a semiconductor laser, or other laser system producing a plurality of wavelengths, either electrically or optically pumped, can be provided as the laser source 12 in the system 10 described herein with an output power of at least 100 mW and preferably in excess of 200 mW. The laser source 12 can instead be a MicraChip® Nd:YAG CW laser source, such as model number MC-HM-12-00-FONS, manufactured by Micracor, Inc.

In another embodiment shown in FIG. 20A, a system 700 is provided which takes advantage of the multimode operation of a solid state laser described above to provide at least two wavelengths which can be separately modulated using the external modulation system detailed above to provide multiple communication services. The system 700 includes at a central site 702, a laser source 712, an optical amplifier 713, a splitter 18, wavelength division multiplexers (WDMs) 714 and 716, and external modulators 722, 723, 724 and 725. Remote from the central site 702 are an optical amplifier 720, a WDM 718, optical detectors 730, radio base stations 726, 728, wireless terminal 732 and mobile unit 734.

The output of laser source 712, nominally 100-300 mW, is amplified by optical amplifier 713 to provide optical signal S10. The optical amplifier 713 can be a Praseodymium doped fluoride fiber gain module, such as the Fluorolase® Fiber Gain Module manufactured by Galileo Electro-Optics Corporation, a Raman amplifier, or any other suitable gain module. The laser source 712 in multimode operation provides an optical signal S10 having multiple longitudinal modes at wavelengths λ_1 - λ_m. The number of modes provided depends on the geometry of the laser and can be, for example, 4, 8 or 16 modes. Having a number of modes in the range of 4-8 is preferred. In one embodiment, the wavelength is nominally 1319 nm with spacing on the order of 1Å. A 1xN splitter 18 coupled to the optical amplifier 713 splits the optical signal S10 to N outputs SA_1 to SA_N. Output SA_1 is coupled to a WDM 714 which divides the optical signal according to its constituent wavelengths λ_1 - λ_m to separate the wavelengths at the m outputs. The outputs of WDM 714 are coupled to external modulators 722, 723. Outputs SA_{N-1}, SA_N from splitter 18 are coupled to external modulators 724, 725 respectively.

The WDMs are of the type which can operate on densely spaced wavelengths. U.S. Patent No. 4,715,027, incorporated herein by reference, discloses an echelon grating device suitable for handling channel separations on the order of 1Å. Alternatively, the WDMs can be of the ring resonator type.

External modulator 722 receives an optical carrier signal at wavelength λ_1 from WDM 714 and modulates the carrier signal with an RF information signal such as a CATV or telephony signal to provide a modulated output signal 727. External modulator 723 similarly operates on an optical carrier signal at wavelength λ_m to provide a modulated output signal 729. The modulated output signals 727, 729 are coupled to WDM 716 along with modulated output signals associated with the other respective wavelengths output from WDM 714 to provide a wavelength division multiplexed optical signal carried on a fiber optical link 738 to a remote subscriber location 704. At subscriber location 704, an optical amplifier 720 amplifies the optical signal received on link 738. A WDM 718 coupled to the output of the optical amplifier 720 demultiplexes the combined optical signal. The demultiplexed optical signals at wavelengths λ_1 - λ_m are then detected separately by detectors 730. By this approach of modulating separate wavelengths, a subscriber location can be provided with multiple services from a single laser source over a single fiber.

External modulator 724 receives an optical carrier signal SA_{N-1} from splitter 18 and modulates the carrier signal with an RF information signal such as a cellular or personal communications services (PCS) signal to provide a modulated output signal 740. External modulator 725 in a similar manner operates on an optical carrier signal SA_N to provide a modulated output signal 742. The modulated output signals 740, 742 are carried on fiber optical links

to individual radio base stations 726, 728 respectively at locations remote from central site 702. The base stations include optical detectors which convert the optical signals to RF signals for transmission to wireless terminal 732 and mobile unit 734. It should be noted that for upstream transmission of information signals from remote base stations 726, 728 and from the subscriber location 704 towards central site 702, the embodiment illustrated in FIG. 19 can be used.

Conventional transmission practice dictates down conversion of the information signal from an RF carrier frequency to an intermediate frequency (IF) before electro/optical conversion occurs in the central site 702. The down conversion process limits the bandwidth and creates a non-coherent transmission scheme. Down conversion also adds system noise that inhibits spread spectrum transmission which requires recorrelation of the signal from signal noise. The system of the present invention avoids the need to down convert and instead allows the RF information signal to be directly converted to an optical signal through external modulators.

In other embodiments of the system 700, the laser source can be the MicraChip laser model MC-HM-12-00-FONS which provides 4 or more longitudinal modes. The laser source can instead operate at a nominal 1550 nm in which case Erbium doped amplifiers can be used for the optical amplifiers 713, 720.

Referring now to FIG. 20B, there is shown another embodiment of a system configuration that takes advantage of the multimode operation of the sold state laser to enhance the optical distortion correction described hereinabove with respect to FIGs. 2A-2C and FIG. 3. The multimode laser source 712 provides an optical signal S12 having multiple longitudinal modes at wavelengths λ_1 to λ_m. The optical signal S12 is coupled to a WDM 748 which is

adapted to divide the optical signal into two output signals 749, 751 according to wavelength. Output signal 749 includes a portion of optical signal S12 at wavelengths λ_1 to λ_{k-1} while output signal 751 contains a portion with wavelengths λ_k to λ_m.

The wavelength division is selected to provide a majority of the optical power along a first line and a minority along a second line, preferably approximately an 80/20 split in optical power between lines 749 and 751. By attenuating one of the lines 749, 751 further, a more precise 80/20 split can be realized.

The output signals 749, 751 are coupled to external modulators 750, 752 respectively which are configured as primary and secondary modulators to provide optical cancellation of third order components in the modulated output signal 757 of combiner 754. The configuration of FIG. 20B improves the optical distortion correction by providing line spreading of the optical signal. By separating the multimode optical signal S12 into signals 749, 751 having different wavelengths λ_1 - λ_{k-1} and λ_k-λ_m respectively, outputs signals 753, 755 from modulators 750, 752 become quasi non-coherent with respect to each other. This effectively provides line spreading of the combined signal 757.

Referring now to FIG. 21, a communication system 810 is shown which illustrates the principles of the present invention. The system 810 generally comprises optical transmitters 812, dense wavelength division multiplexers 814 and 822, optical amplifier 818 and optical receivers 824. The optical transmitters 812, described in more detail below, output optical information signals 813 each at a different wavelength (λ_1, λ_2...λ_N). The optical information signals 813 are coupled to the WDM 814 which multiplexes the signals to produce a composite optical signal 815 at its output. The composite optical signal 815

includes the optical information signals at the input wavelengths λ_1-λ_N. The WDM 814, described in detail further below, is a dense WDM that includes narrowband interference filter technology to achieve channel spacing on the order of two nanometers or less.

The composite optical signal 815 is coupled to the optical amplifier 818 which provides optical gain. The optical amplifier 818 is preferably an erbium-doped fiber amplifier such as an Italtel AF18A device which provides 18dBm output power. The amplified composite optical signal 819 is coupled to a remote dense WDM 822 over fiber transmission link 821. The fiber transmission link 821 in the preferred embodiment is a CATV long-haul fiber trunk. The remote WDM 822 demultiplexes the composite optical signal to its constituent optical information signals 823 at the respective wavelengths λ_1-λ_N. The optical receivers 824 each receive a particular optical information signal 823.

Stimulated Brillouin scattering (SBS) is a phenomenon which limits the amount of optical power that can be effectively coupled into a fiber. SBS is particularly difficult in external modulation systems which use an optical source having a relatively narrow optical linewidth. To further exacerbate the problem, systems which employ optical amplifiers can produce gain which surpasses the SBS threshold, typically about 8 dBm in single mode fiber. It should be noted that SBS is a function of spectral linewidth and power and is not dependent on wavelength per se. Willems, F.W. et al., "Harmonic Distortion Caused By Stimulated Brillouin Scattering Suppression in Externally Modulated Lightwave AM-CATV Systems," IEEE Electron. Lett., vol 30, pp. 343-345, Feb. 1994, and Willems, F.W. et al., "Simultaneous Suppression of Stimulated Brillouin Scattering and Interferometric Noise in Externally Modulated Lightwave AM-

SCM Systems," IEEE Photon. Tech. Lett., vol. 6, No. 12, pp. 1476-1478, Dec. 1994, describe the use of single tone phase modulation applied at frequencies above twice the highest CATV carrier frequency to increase the spectral linewidth of the optical signal and thereby increase the SBS threshold. These references only describe experimental setups and suggest that practical systems may require relatively high electrical powers to achieve the necessary phase modulation index.

It is well known for a phase modulator that the magnitude of $V\pi$, the voltage at which the phase modulation index equals π, is inversely dependent on electrode length of the phase modulator device. A phase modulator located on a substrate that includes a Mach-Zehnder modulator will have short electrodes and therefore require a large $V\pi$. The preferred embodiment of the present invention instead utilizes a separate phase modulator which can have longer electrodes so that a lower $V\pi$ is required. Further, instead of coupling an individual phase modulator to the output of each optical transmitter in the system 810, a single phase modulator 816 is coupled to the output of the dense wavelength division multiplexer 814.

The SBS suppression circuitry in the preferred embodiment will now be described. The system 810 includes a practical low cost oscillator circuit 830 which generates a single tone modulation signal 831. The oscillator circuit 830 is described in more detail below. The single tone modulation signal 831 is applied to the phase modulator 816 to modulate the composite optical signal 815. The phase modulator 816 provides an optical signal 817 having a number of optical carriers equally spaced in frequency which thereby increases the spectral width of the optical signal. Thus, the phase modulation increases the total power that can be injected into the fiber transmission system before the onset of SBS, thereby

increasing the SBS threshold. The single tone modulation signal 831 of oscillator 830 is selected to have a frequency above twice the highest CATV subcarrier frequency to avoid any significant intermodulation distortion from occurring. The preferred frequency for the single tone modulation signal 831 is in the range from about 1.8 GHz to 5 GHz.

The system 810 includes optical receiver 826 coupled to the amplified composite optical signal 819 through a splitter 820. A portion 825 of the amplified composite optical signal 819 is detected in the optical receiver 826 and fed back to a threshold detector 828 which detects the level of Relative Intensity Noise (RIN) and adjusts the output level of the single tone modulation signal 831 provided by oscillator circuit 830 to increase the SBS threshold as required. It should be noted that increasing the SBS threshold too much can cause dispersion effects in the system and thus the feedback is useful in maintaining the oscillator circuit output such that the SBS threshold is increased only as needed. The optical receiver 826 also provides a feedback signal to the optical transmitters 812 for bias control. The optical transmitters 812 include bias control circuitry which is described further below.

Referring to FIG. 22, the optical transmitter 812 is there shown. The optical transmitter 812 includes a DFB laser source 834 operating as a continuous wave laser source, an external modulator 838, an RF driver 840, a frequency filter 842, and a bias control circuit 844. The DFB laser source 834 provides an optical signal 835 to the external modulator 838. The optical signal 835 is coupled to external modulator 838 which is preferably a Mach-Zehnder modulator formed in lithium niobate. The external modulator 838 is driven by RF driver 840 with an RF information signal 839 to intensity modulate the optical signal 835 and provide optical information signal 813 at

its output. The external modulator 838 is maintained at the quadrature point $V\pi/2$ with bias control signal 845 from bias control circuit 844.

The DFB laser source 834 provides 6 mw of power at a nominal wavelength in the range of 1530 to 1565 nm. Across the optical transmitters 812, the wavelengths of the DFB laser sources 834 are preferably separated by about 1.6 nm. The DFB laser source includes a laser controller that employs thermal control to maintain wavelength alignment to the dense WDM 814 (FIG. 21). In addition, a feedback loop is employed to further maintain wavelength alignment. A supervisory dither tone f_0 is injected at the external modulator 838 on line 837. The feedback signal 827 provided by optical receiver 826 is filtered by frequency filter 842 and provided to the laser controller 836 on line 843 which adjusts the DFB laser to maximize the level of the received dither tone f_0. The dither tone f_0 is different for each of the optical modulators 812 to provide for proper discrimination and wavelength alignment. The dither tones are preferably in the range of 4 to 6 MHz.

Because the continuous wave laser source 834 does not produce chirp, the external modulation can be monitored with a single receiver 826 to provide both SBS feedback correction and bias control. A key feature is that the SBS correction is line length independent.

Referring now to FIG. 23, a preferred embodiment of a dense WDM 814 is there shown. The dense WDM is preferably a device manufactured by Optical Corporation of America. The WDM 814 in FIG. 23 is illustrated as a four channel dense WDM. The WDM 814 comprises multi-cavity MicroPlasma environmentally stable filters (ESF™) 860. Lenses 862 are used to collimate input light before directing the signals at a slight angle through an AR coated facet to filters 860. Wavelengths of light which are inband of the narrowband filter transmit through the filter 860 and all

other wavelengths are reflected. In this manner, light cascades in reflection from filter to filter 860 down the device, and with each reflection, a single wavelength is added.

Referring to FIG. 24, a filter 860 in the device 814 of FIG. 23 is shown. The narrowband interference filter 860 is, as noted above, a multi-cavity filter comprising a spacer 870 surrounded by dielectric or metallic reflecting stacks 872. The filter 860 transmits at a wavelength at which the spacer 870 defines a Fabry-Perot cavity that has a spacing of an integral number of halfwaves. Thus, the reflecting stacks 872 are spaced accordingly to achieve a particular filter wavelength. A two-cavity device is shown in FIG. 24 in which a second spacer 870' is surrounded by dielectric or metallic reflecting stacks 872 and 872'. Metal oxide or metal reflecting coatings are used in these filters to provide improved thermal stability over the operating range of the system, where the layers are formed by plasma deposition. Further details regarding the characteristics of these filters can be found in "Improved Temperature and Humidity Stability of Ultra-Narrow Band Filters" by Scobey and Stupik in the 37th Annual Technical Conference Proceedings (1994) of the Society of Vacuum Coaters, the entire contents of which is incorporated herein by reference. Metal oxide mirrors that are temperature and humidity stable may also be fabricated using ion-assisted deposition techniques.

Another WDM that can be used in conjunction with the present invention is an echelon grating system described in greater detail in U.S. Patent No. 4,715,027, the entire contents of which is incorporated herein by reference.

Referring now to FIG. 25, an embodiment of the oscillator circuit 830 is shown. The oscillator circuit 830 includes a coaxial resonator CR_1. The coaxial resonator CR_1 is preferably a coaxial ceramic resonator

having a shorted end face which functions as a quarter wave resonant line circuit. The ceramic resonator is preferred over other coaxial line resonators because of its smaller size dimensions, higher Q, and better high temperature stability. The ceramic resonator CR_1 can be, for example, a device supplied by Alpha or Kyocera. The required oscillator frequency in the range of about 1.8 GHz to 5 GHz is obtained by using an appropriate resonator and by fitting suitable capacitor and inductor elements. The amplifier A1 is tuned appropriately to provide a high Q. A composite ceramic resonator with dual coefficients is preferred for stability. The low cost design of the oscillator circuit 830 provides a pure tone for an effective implementation. The output level of the oscillator circuit 830 is controlled by a control signal 829 received from threshold detector 828 (FIG. 21).

In analog lightwave communication systems which use external modulation, bias control of the external modulator can be achieved by injecting supervisory tones and monitoring the output optical signal for second order products of the supervisory tones. It is important to note that some CSO, for example, at -80 dBc is useful for bias control

Referring now to FIG. 26, the automatic bias control circuit 844 there shown is a second harmonic detector that includes a mixer FM IF integrated circuit 880 which is preferably a Phillips NE605D integrated circuit. The NE605D is a combination mixer and FM receiver which includes a received signal strength indicator (RSSI).

The second order distortion can be prevented by biasing the external modulator 838 (FIG. 22) at 1/2 of the half wave voltage otherwise known as V_π. Since the optimum bias point can drift with temperature, the system must use a control loop to actively keep the bias adjusted to the optimum level.

The amplitude response of the second harmonic versus control voltage has a "V" shape. The ABC circuit detects the slope to determine which direction to adjust the bias voltage. A positive slope indicates that the voltage is to the right of the minimum and must be decreased. A negative slope indicates that the bias is to the left of the minimum and must be increased.

The ABC circuit accomplishes this by using a dither signal. This is a very small (≈30mV) AC signal which is superimposed on the modulator DC bias shown in FIG. 22 at line 837. Since the bias is moving, the second harmonic level will also move slightly which in turn causes a change in the RSSI level. If the DC bias is lower than the optimum voltage, the RSSI will decrease when the dither signal is positive, and increase when it is negative.

A difference amplifier operates, when the DC voltage is too low, such that the positive delta is multiplied by -1 and the negative delta is multiplied by +1. This results in an error signal which is negative. This error signal is then input to an inverting integrator. Therefore, the output from the integrator will be positive and the bias will move towards the optimum voltage. The same explanation is used when the DC bias is greater than optimum, with the obvious exception that the circuit will decrease the bias voltage.

Ideally, when the loop is locked, the output should be a pure DC signal. A real circuit will produce some very small residual error signal, mostly due to the non-ideal performance of the difference amplifier.

The noise level input to the receiver is approximately -97dBm in a 3kHz BW. This translated into -93dBm in a 7.5kHz BW. Since the input level of the second harmonic, when nulled, is approximately -95dBm, the system is working with a S/N ratio less than 0.

The system will still work due to two important factors:

- It is only necessary to see a change in RSSI for a change in second harmonic level.
- The integrator BW also lowers the noise equivalent BW and allows the system to perform in poor S/N environments.

The ultimate performance of the loop is really limited by the change in RSSI for a given change in signal level. The following table shows the total power change for various S/N ratios for a 1dB change in input signal level.

S/N dB	Δ Power dB
+3	+0.60
+2	+0.59
+1	+0.47
0	+0.47
-1	+0.41
-2	+0.36
-3	+0.31
-4	+0.26
-5	+0.22
-6	+0.18

This table is important as it demonstrates that for negative S/N ratios, it is still possible to see a change in RSSI for a change in input level (i.e., change in the level of the second harmonic of the pilot tone). However, the RSSI has a sensitivity of 40m V/dB so at an S/N level of -6dB, the RSSI change will only be 8mV. This means that op-amp offset errors become very important to the operation of the loop.

It is very important that rejection of the fundamental is sufficient to prevent the fundamental from generating a second harmonic in the receiver which would cause problems for the loop. The second order intercept must be high enough to prevent this from happening.

The receiver section uses an IF of 10.7 MHz to allow for the use of standard crystal filters. The input signal, which is the second harmonic of the test tone, is 3.6864 MHz. This signal is converted to 10.700 MHz by a high-side mix with the 14.3864 MHz oscillator. Due to the narrow BW of the crystal filters a custom crystal is necessary to keep the oscillator at the correct frequency.

In order to maintain the signal within the passband of the crystal filters, the total frequency error must be kept less than 350 ppm. The oscillator crystals are 150 ppm over temperature, leaving a 200 ppm error allowed in the 1.8432 MHz crystal. These values are within standard tolerances.

The mixer has a very high input impedance (~4.5kω) so an optimum match to 500 is difficult. For simplicity a tapped-C match is used. The image frequency protection needs to be reasonable (≥ 20dB), since the second order products from the CATV signals may end up falling at the image and interfering with proper operation of the loop. In order to maintain reasonable Q of the circuit, the input match must be tuned by adjusting a trim cap. The capacitor simply needs to be tuned to maximize RSSI.

The local oscillator is a Colpitts configuration using the NE605 oscillator transistor, a 14.3864 MHz crystal, and 2 capacitors. The peak-peak level at the input to the NE605 is approximately 200mV. Due to the high level of incoming noise caused by the laser/modulator, it is also important to use a narrow BW. The current configuration uses crystal filters of ±3.75 kHz BW.

Alternatively, it is well known that discrete frequencies are already available in a CATV signal spectrum that can analyzed for distortion. For example, channels 3 and 4 are typically available as carrier frequencies at 61.25 MHz and 67.25 MHz respectively since they are generally required for signal conversion at a CATV set top

box. The second order products fall +/-1.25 MHz away from the carrier frequencies. Additionally, channels 5 and 6 produce CSO at 4.5 MHz and 6 MHz respectively. A heterodyne approach can be used to take advantage of the available carrier frequencies and obviate the need for injecting supervisory tones.

Referring now to FIG. 27, another preferred embodiment of a dense WDM 900 is there shown. The WDM 900 in the configuration shown provides a 1 to 8 wavelength division demultiplexing function. An input fiber 902 is terminated at a ferrule 906A. Output fibers 904 terminate on ferrules 906B. A pair of lenses 908 are positioned adjacent each ferrule 906A, 906B. The lenses 908 are used to collimate input light from fiber 902 which is also directed at a slight angle through a channel 916. The input light 922 is transmitted along channel 916 to an interface with a plate 910 on which is deposited filter material 924 which segregates desired frequencies by transmitting light 926 at one wavelength and reflecting the remaining light back through angled channels 914. Thus, wavelengths of light which are inband of the narrow band filter 924 are transmitted through the filter and all other wavelengths are reflected. In this manner, light cascades in reflection from filter to filter 924 through the device 900. A second filter plate 912 is positioned parallel to the plate 910 to filter light reflected back from plate 910. The filters 924 are selected to provide a narrowband filtering of the wavelengths of interest, such as the multimode wavelengths noted above.

FIG. 28 is a perspective view of a portion 920A of the dense WDM 900 which shows the angled channels 916, 914. A reflective coating may optionally be deposited in the channels 914, 916 to help channel the light and prevent cross talk between channels. The block 920A can be a machined metal block or an injection molded plastic

material with filter plates or arrays 910, 912 mounted on both sides. Slots to contain and house the ferrules 906A, 906B, the lenses 908 as well as the filter plates 910, 912 can also be included to provide accurate alignment of components upon assembly.

A key aspect of the configuration of FIG. 27 is the inclusion of an anti-reflective coating on the lenses 908 which eliminates or reduces loss due to reflection as light is introduced into the device. By reducing loss due to reflections to less than 1%, more optical power can be passed through such configurations. In a power splitter, the filter plate 910 is adapted to pass and reflect a single frequency with a power split ratio selected by design.

Other applications for the dense WDM configuration 900 include power splitters and WDMs. Referring now to FIG. 29, a device 950 is shown which can be configured as a WDM or a power splitter, depending on the selection of a filter plate 962. Input light received on fiber 952 is collimated through lens assembly 958 to provide a beam 960. If the device 950 is fabricated as a power splitter, a portion of beam 960 is designed as beam 968 and the remaining portion is passed through filter 962 as beam 970. Beams 968 and 970 are collimated through assemblies 966, 972. If the device 950 is instead configured as a WDM, input beam 960 contains light at two wavelengths, for example, 1330 and 1550 mm. At filter 962, one of the wavelengths is passed as beam 970 and the other wavelength is reflected as beam 968.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

CLAIMS

What is claimed is:

1. An lightwave communication system comprising:

an optical source for providing optical information signals at different wavelengths;

a wavelength division multiplexer having an input for receiving the optical information signals from the optical source and for multiplexing the optical information signals, the multiplexer including a filter system to provide an optical output; and

a fiber optic system coupled to the optical output of the wavelength division multiplexer for receiving an output optical signal.

2. The system of Claim 1 wherein the optical source comprises a plurality of DFB lasers which each provide a continuous wave optical signal; an external modulator coupled to each laser source having an RF electrical input; and an RF driver coupled to the RF electrical input of the external modulator which provides an RF information signal for modulating the continuous wave optical signal to produce the optical information signal.

3. The system of Claim 1 further comprising:

an oscillator circuit providing a single tone modulation signal;

a phase modulator having an optical input coupled to the output of the wavelength division multiplexer for receiving a composite optical signal and an electrical input coupled to the oscillator circuit for receiving the single tone modulation signal, the single tone modulation signal driving the phase

modulator to modulate the composite optical signal such that stimulated Brillouin scattering threshold in the system is increased.

4. The system of Claim 3 further comprising an optical receiver coupled to the output of the phase modulator for receiving a portion of the phase modulated composite optical signal and a noise threshold detector coupled to the optical receiver for detecting noise level in the composite optical signal to control the level of the single tone modulation signal.

5. The system of Claim 2 wherein the RF information signal comprises at least 40 cable television channels.

6. The system of Claim 1 further comprising an optical amplifier coupled between the output of the first wavelength division multiplexer and the fiber optic transmission system.

7. The system of Claim 6 wherein the optical amplifier is an erbium-doped fiber amplifier.

8. The system of Claim 1 wherein the fiber optic transmission system comprises a second wavelength division multiplexer for demultiplexing the composite optical signal to the optical information signals at different wavelengths and at least two optical receivers, each receiver for receiving one of the optical information signals at a respective wavelength.

9. The system of Claim 1 wherein the optical source comprises a DFB laser source that is directly modulated with an RF information signal.

10. The system of Claim 9 wherein the RF information signal comprises at least 40 cable television channels.

11. The system of Claim 1 wherein the wavelength division multiplexer provides a wavelength separation of less than 2 nm.

12. The system of Claim 1 wherein the wavelength division multiplexer comprises an optical waveguide that aligns a plurality of filters of the filter system, the optical waveguide comprising a plurality of channels in a substrate.

13. The system of Claim 1 wherein the wavelength division multiplexer comprises a demultiplexer.

14. The system of Claim 1 wherein the communication system comprises an analog cable television transmission system.

15. An lightwave communication system comprising:

a laser source that provides optical information signals at different wavelengths;

a wavelength division multiplexer having an input that receives the optical information signals from the laser source and multiplexes the optical information signals, the multiplexer including a filter system to provide an optical output;

a plurality of modulators that receive optical output from the multiplexer; and

a fiber optic system coupled to the plurality of modulators.

16. The system of Claim 15 wherein the wavelength division multiplexer comprises an optical waveguide that aligns a plurality of filters relative to an optical path, the optical waveguide comprising a plurality of channels in a substrate.

17. The system of Claim 15 wherein at least a first pair of wavelengths from the laser source are coupled to a first modulator and a second pair of wavelength are coupled to a second modulator.

18. A method of multiplexing a multiwavelength optical signal comprising:

providing an optical source to generate optical information signals at different wavelengths;

providing a wavelength division multiplexer having an input for receiving the optical information signals from the optical source and for multiplexing the optical information signals, the multiplexer including a filter system to provide an optical output;

providing a fiber optic system coupled to the optical output of the wavelength division multiplexer for receiving an output optical signal; and

transmitting multiplexed signals through the fiber optic system.

19. The method of Claim 18 further comprising correcting for distortion in the fiber optic system.

20. The method of Claim 18 further comprising coupling a splitter between the source and the multiplexer.

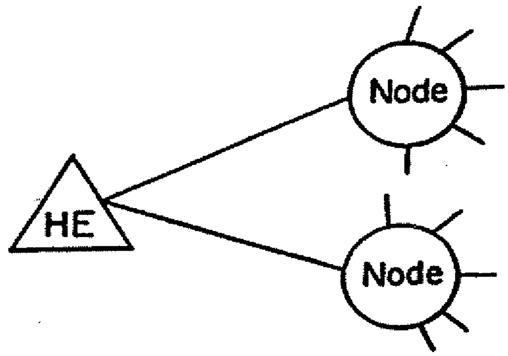


FIG. 1
(Prior Art)

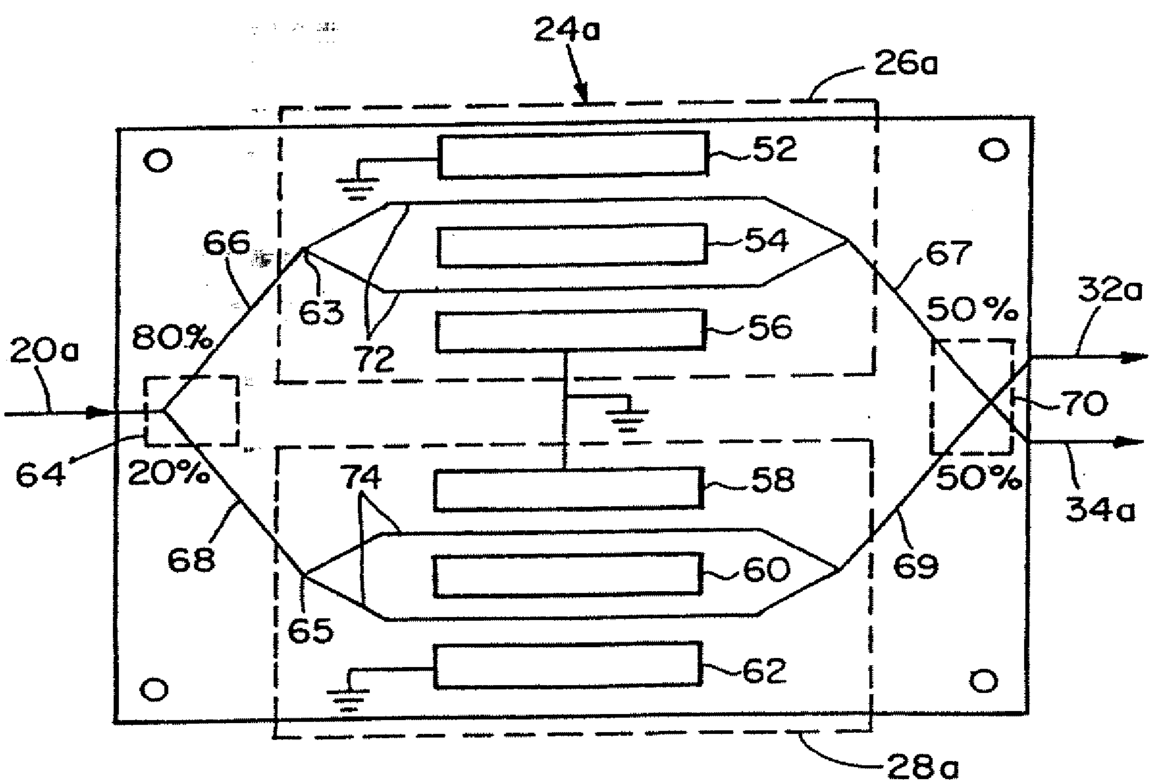


FIG. 3

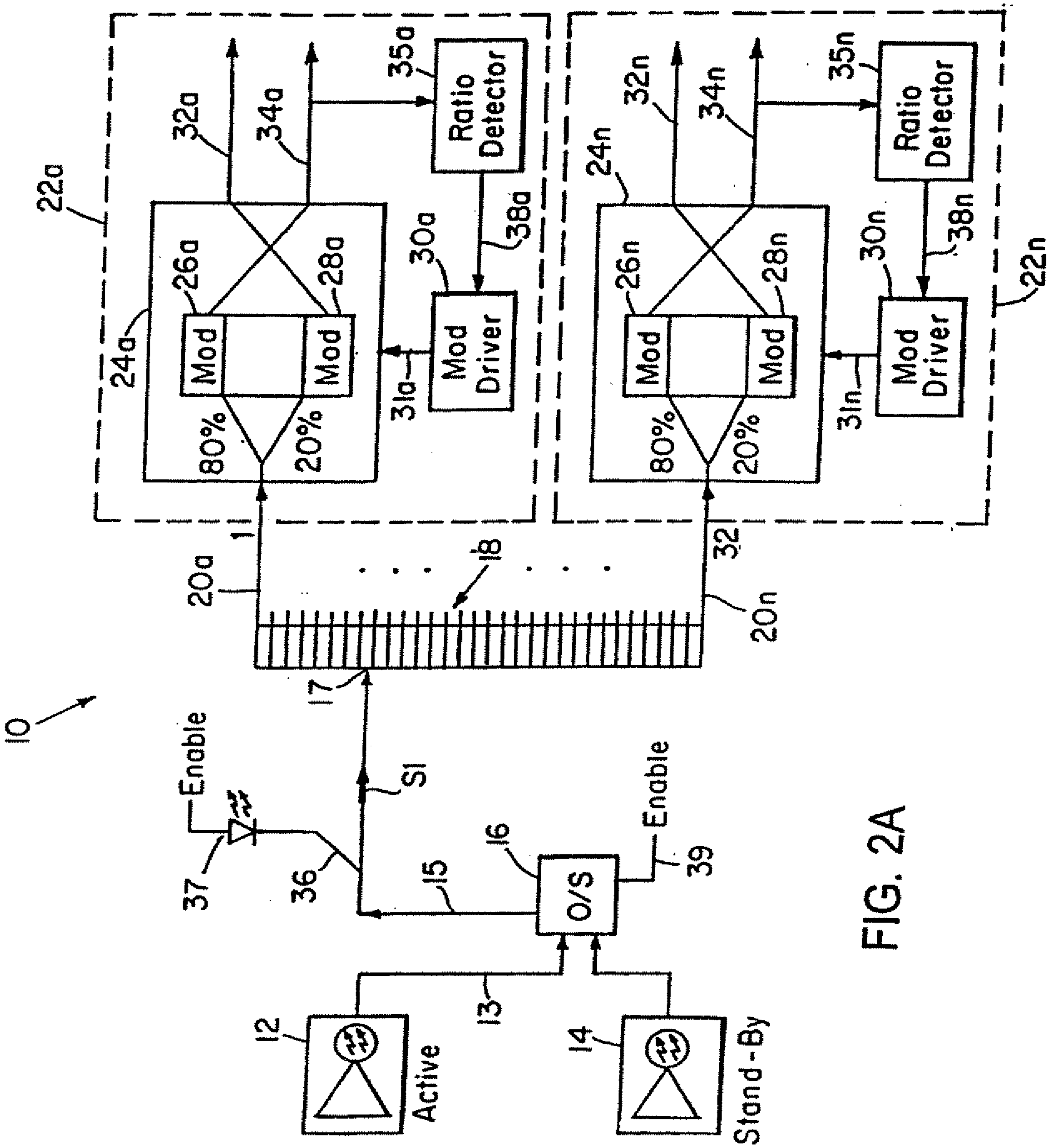

10
Active
12
13
Stand-By
14
O/S
16
15
Enable
39
36
37
Enable
SI
17
18
20a
20n
1
32
22a
22n
24a
24n
26a
28a
26n
28n
Mod
Mod
Mod
Mod
80%
20%
80%
20%
Mod Driver
Mod Driver
30a
30n
31a
31n
Ratio Detector
Ratio Detector
35a
35n
38a
38n
32a
34a
32n
34n

FIG. 2A

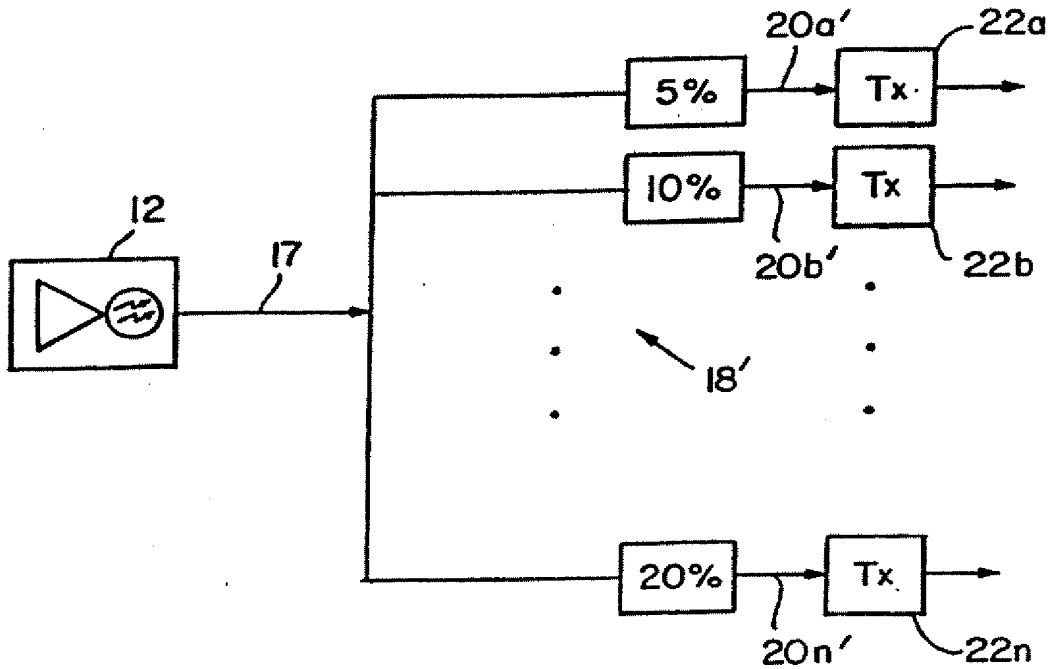

12
17
5%
10%
20%
Tx
Tx
Tx
20a′
20b′
20n′
22a
22b
22n
18′

FIG. 2B

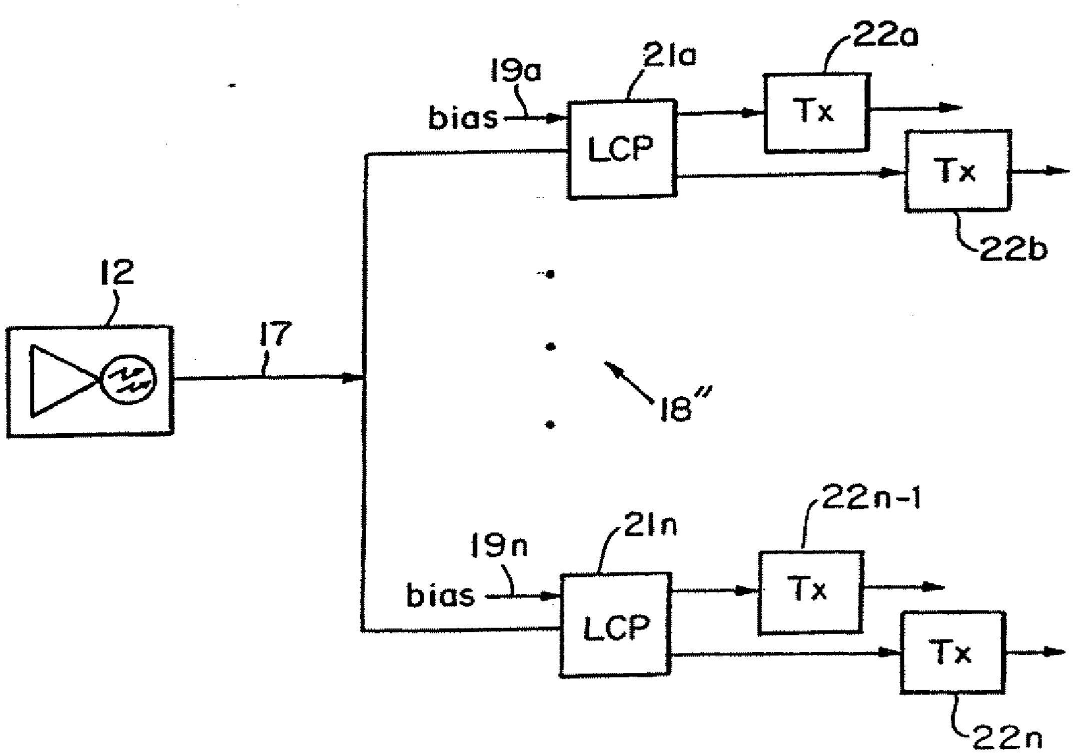

12
17
19a
bias
21a
LCP
Tx
Tx
22a
22b
18″
19n
bias
21n
LCP
Tx
Tx
22n-1
22n

FIG. 2C

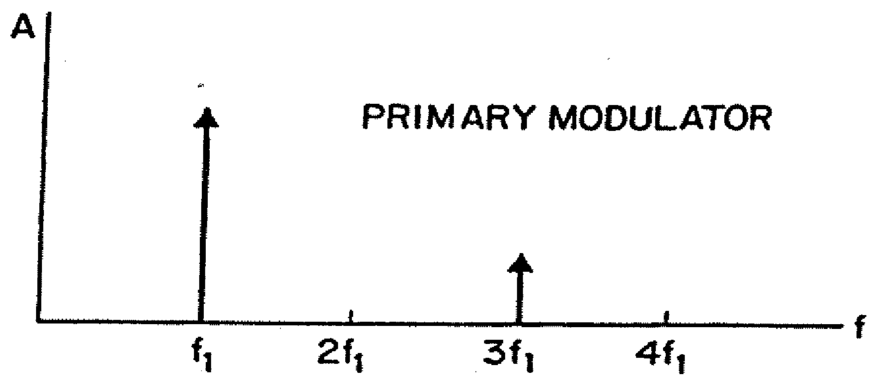


FIG. 4a

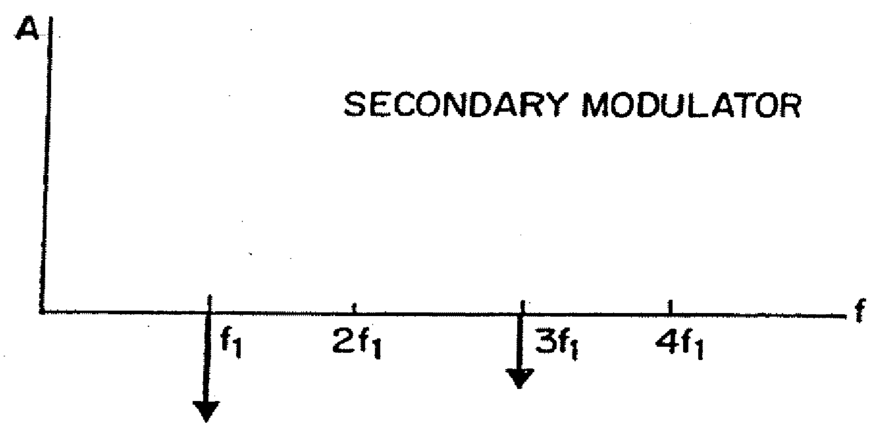


FIG. 4b

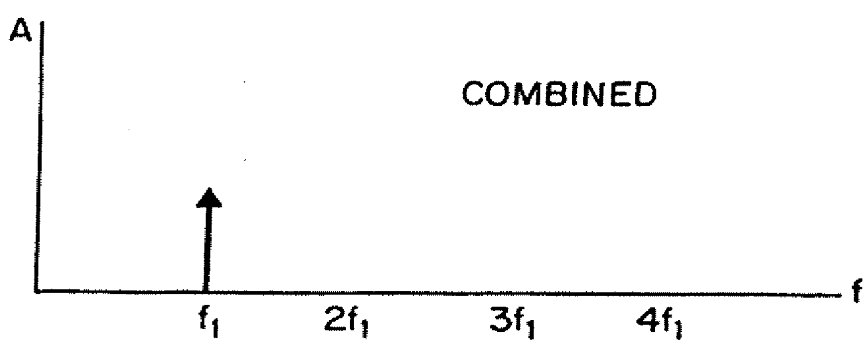
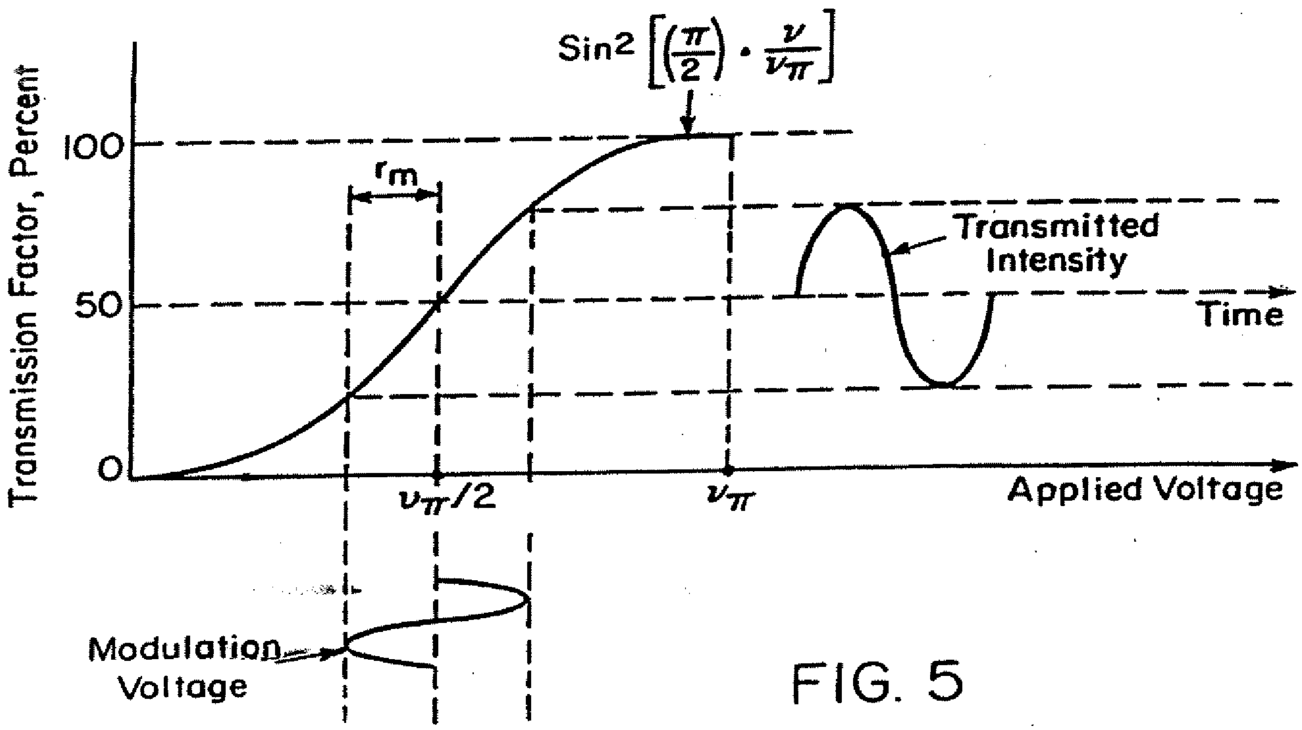
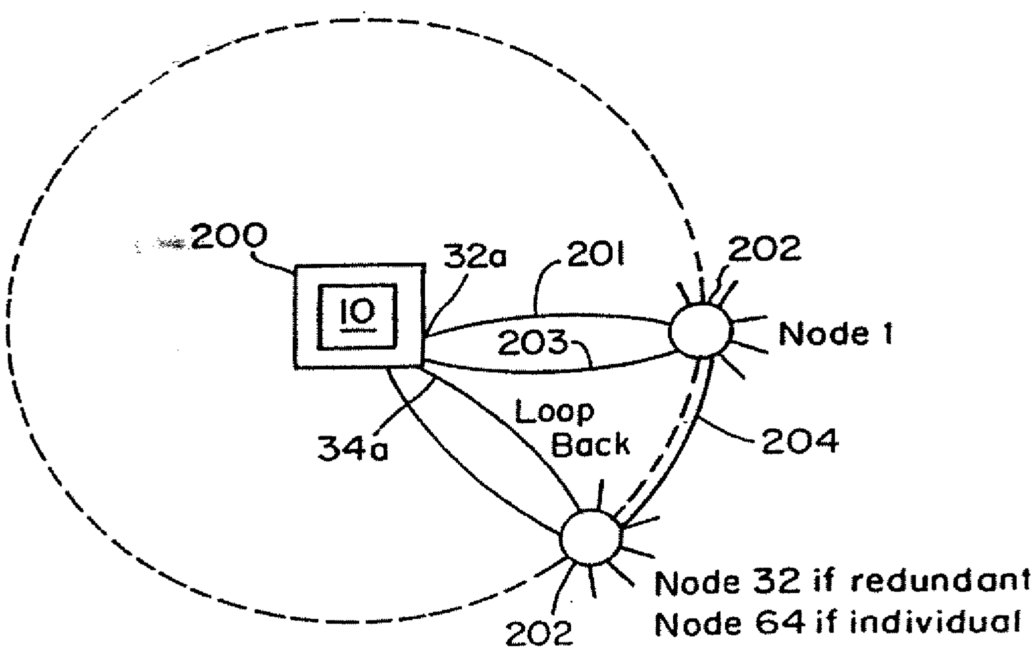


FIG. 4c



$\mathrm{Sin}^2\left[\left(\frac{\pi}{2}\right)\cdot\frac{\nu}{\nu_\pi}\right]$
Transmission Factor, Percent
100
50
0
r_m
Transmitted Intensity
Time
$\nu_\pi/2$
ν_π
Applied Voltage
Modulation Voltage

FIG. 5



200
10
32a
201
202
203
Node 1
Loop Back
34a
204
202
Node 32 if redundant
Node 64 if individual

FIG. 8

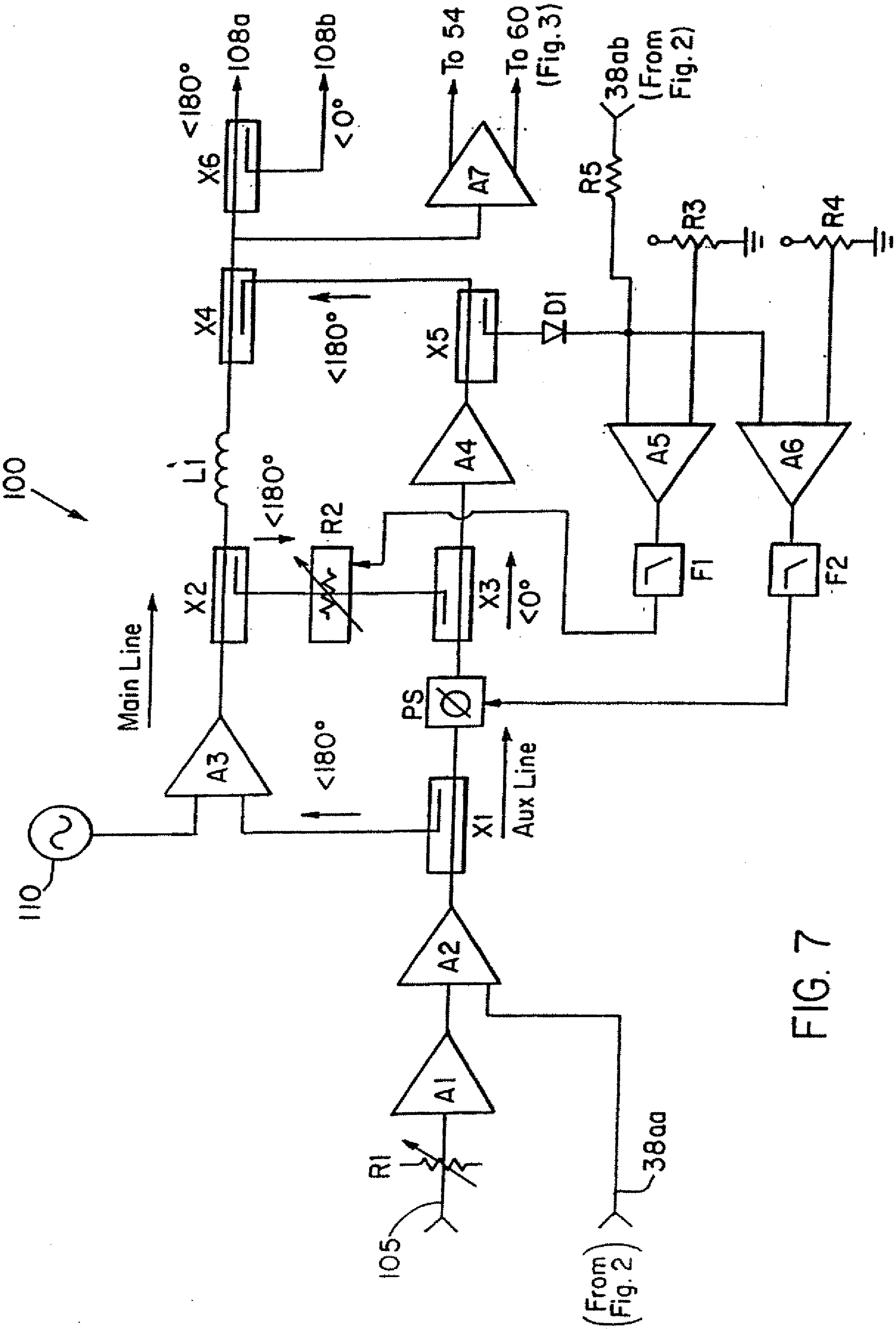

100
110
105
R1
A1
A2
38aa
(From Fig.2)
A3
X1
Aux Line
<180°
PS
Main Line
X2
X3
<0°
R2
<180°
L1
A4
F1
F2
A5
A6
X4
X5
<180°
D1
R3
R4
R5
38ab (From Fig.2)
A7
To 54
To 60 (Fig.3)
X6
<180°
108a
108b
<0°

FIG. 7

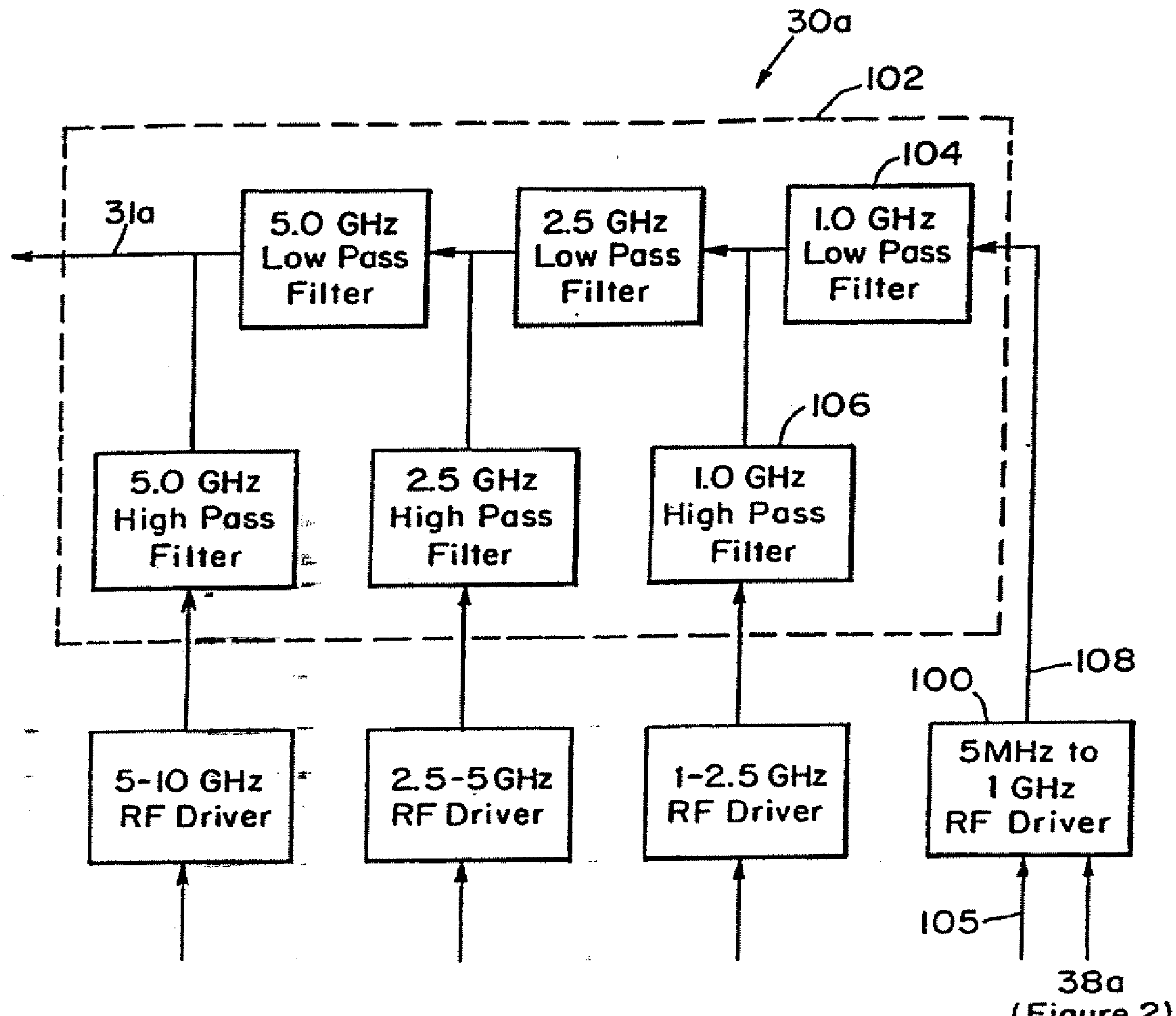

30a
102
104
31a
5.0 GHz Low Pass Filter
2.5 GHz Low Pass Filter
1.0 GHz Low Pass Filter
106
5.0 GHz High Pass Filter
2.5 GHz High Pass Filter
1.0 GHz High Pass Filter
100
108
5-10 GHz RF Driver
2.5-5 GHz RF Driver
1-2.5 GHz RF Driver
5MHz to 1 GHz RF Driver
105
38a (Figure 2)

FIG. 6

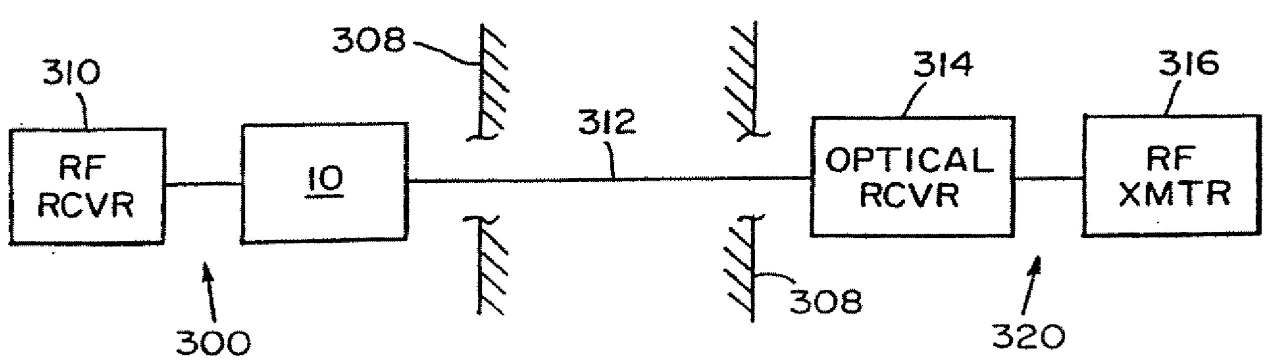

308
310
RF RCVR
10
312
314
OPTICAL RCVR
316
RF XMTR
308
300
320

FIG. 9

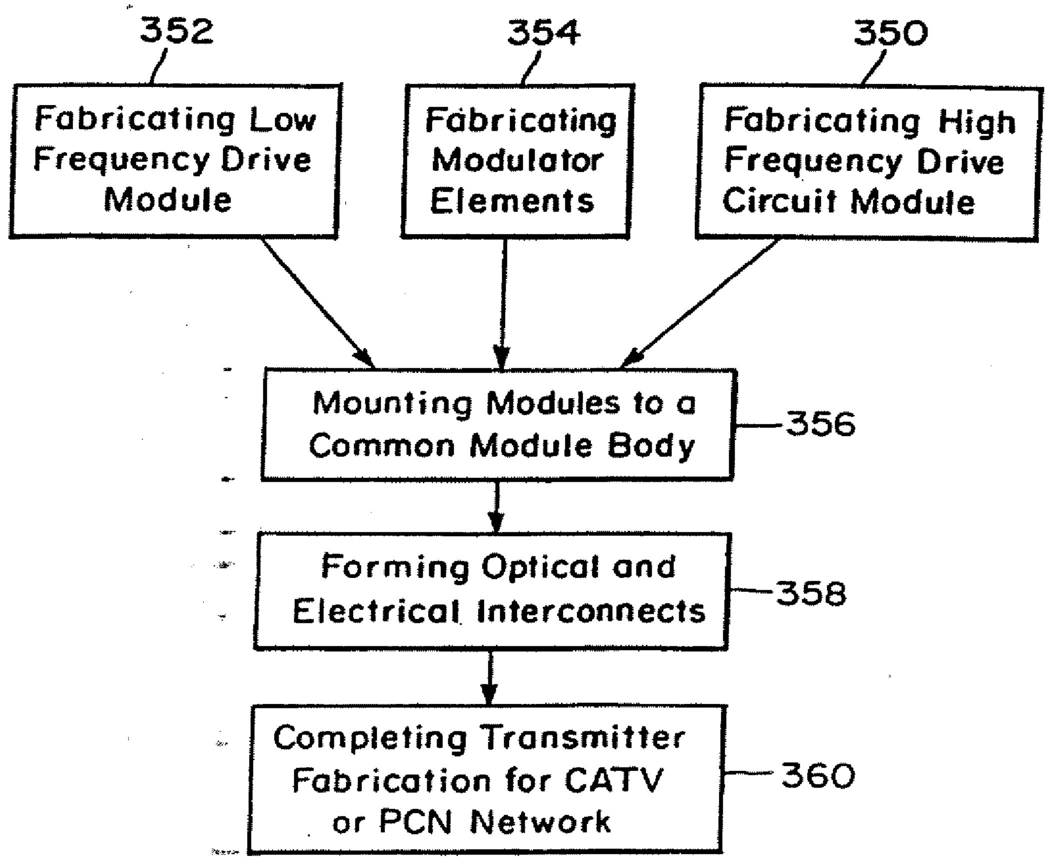

352
Fabricating Low Frequency Drive Module
354
Fabricating Modulator Elements
350
Fabricating High Frequency Drive Circuit Module
Mounting Modules to a Common Module Body
356
Forming Optical and Electrical Interconnects
358
Completing Transmitter Fabrication for CATV or PCN Network
360

FIG. 10

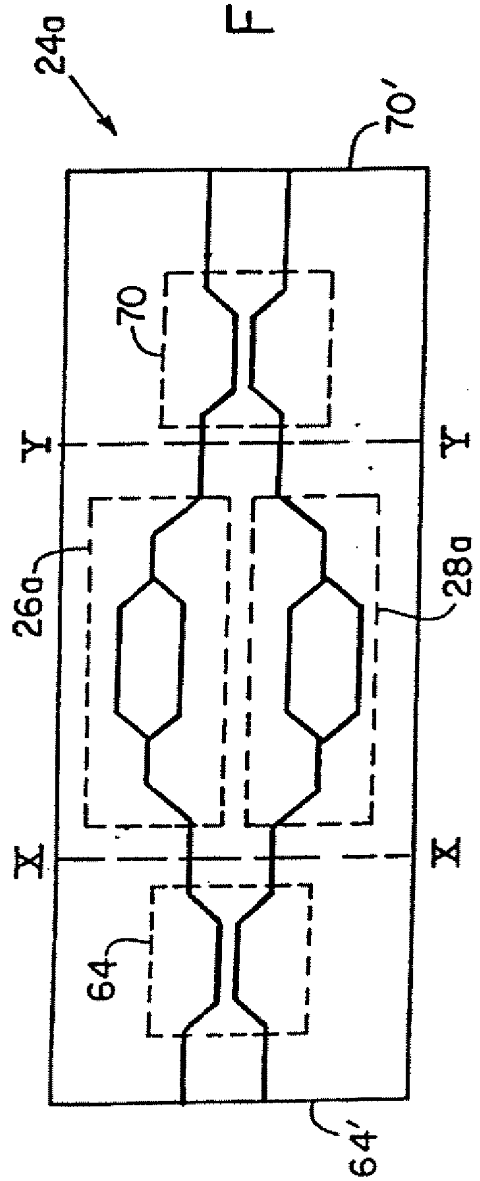

24a
70'
70
Y
Y
26a
28a
X
X
64
64'

FIG. 11

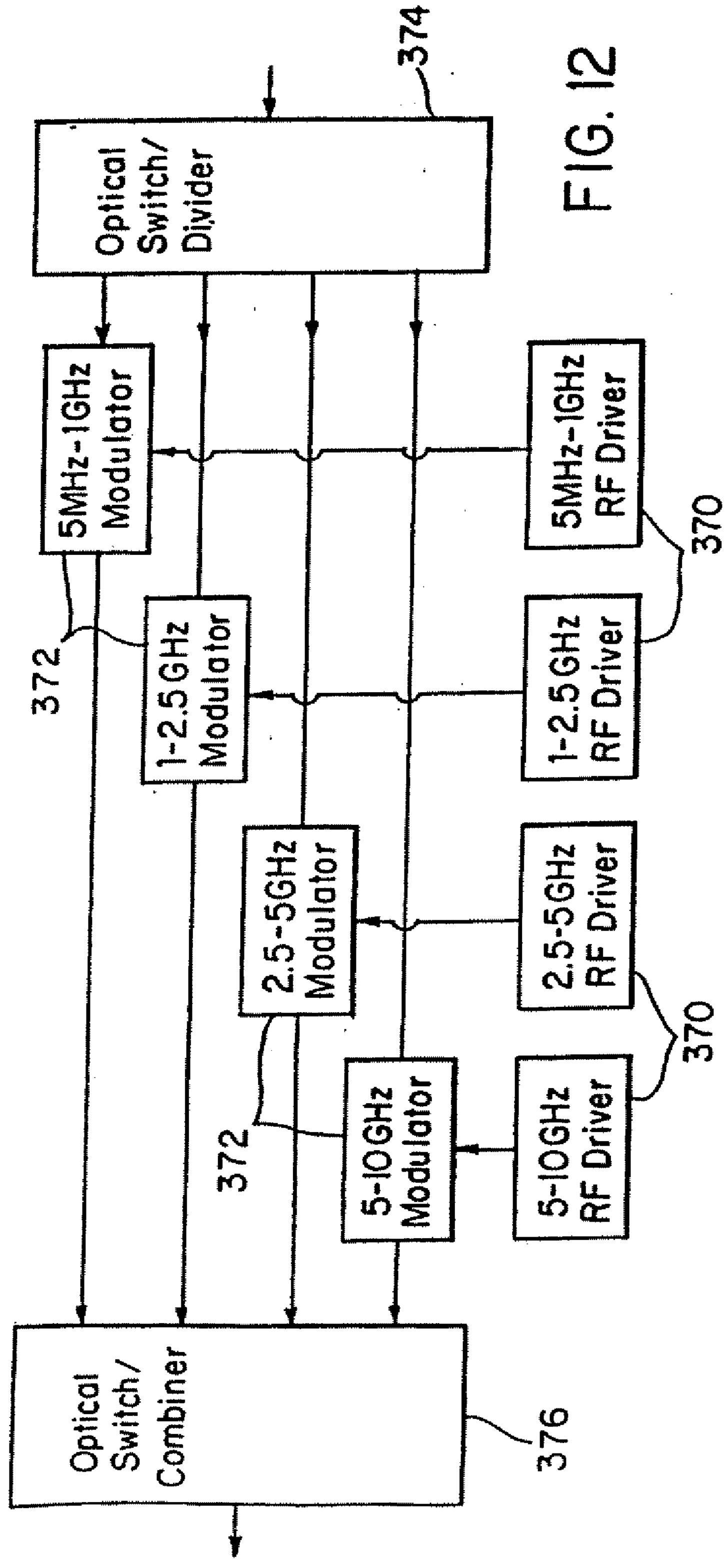

374
Optical Switch/ Divider
5MHz-1GHz Modulator
5MHz-1GHz RF Driver
370
1-2.5GHz Modulator
1-2.5GHz RF Driver
372
2.5-5GHz Modulator
2.5-5GHz RF Driver
370
5-10GHz Modulator
5-10GHz RF Driver
372
Optical Switch/ Combiner
376

FIG. 12

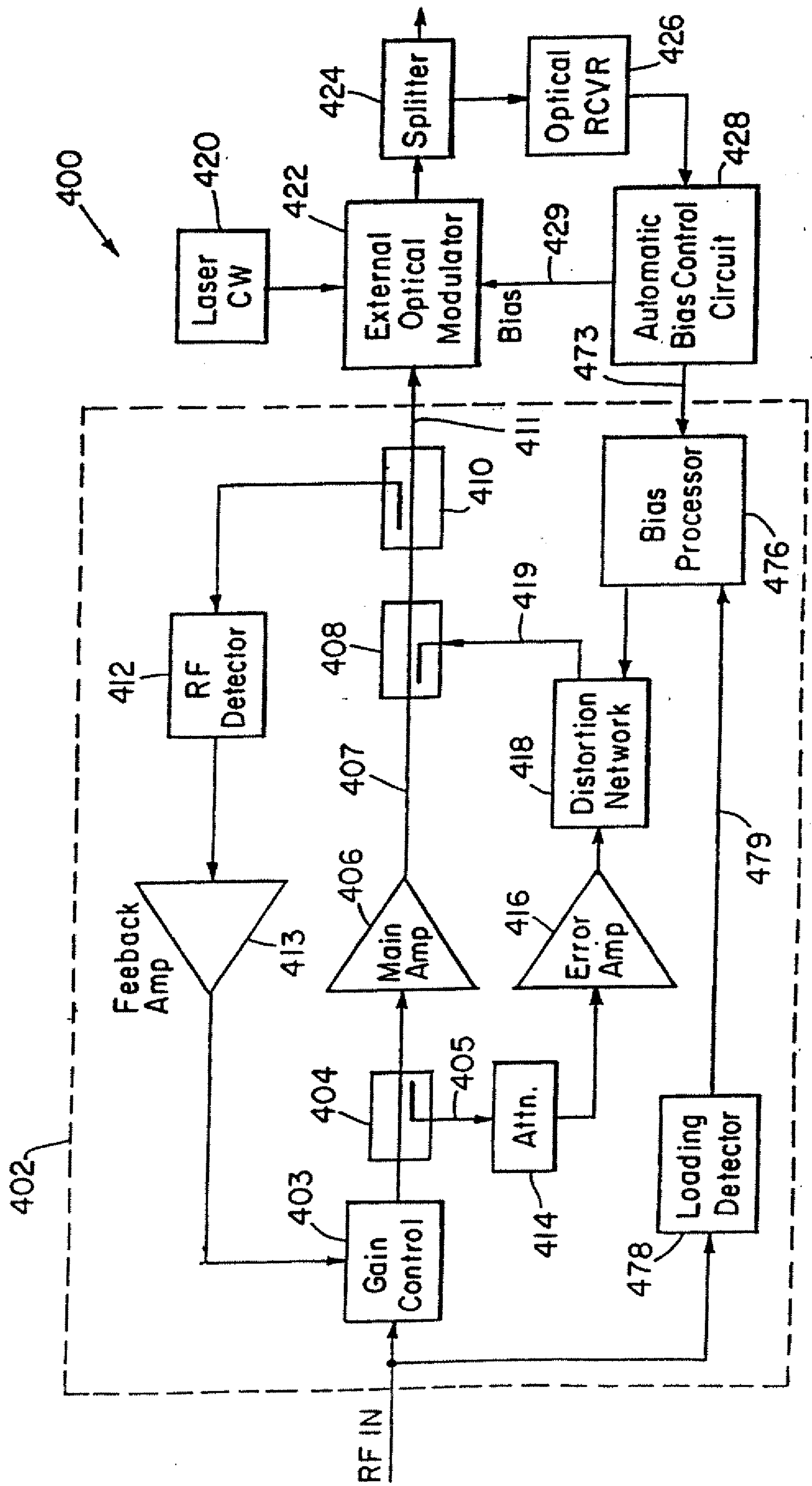

400
Laser CW
420
External Optical Modulator
422
Splitter
424
Optical RCVR
426
Automatic Bias Control Circuit
428
429
Bias
473
411
410
Bias Processor
476
RF Detector
412
408
419
Distortion Network
418
407
Feeback Amp
413
Main Amp
406
Error Amp
416
404
405
Attn.
414
479
Loading Detector
478
Gain Control
403
402
RF IN

FIG. 13

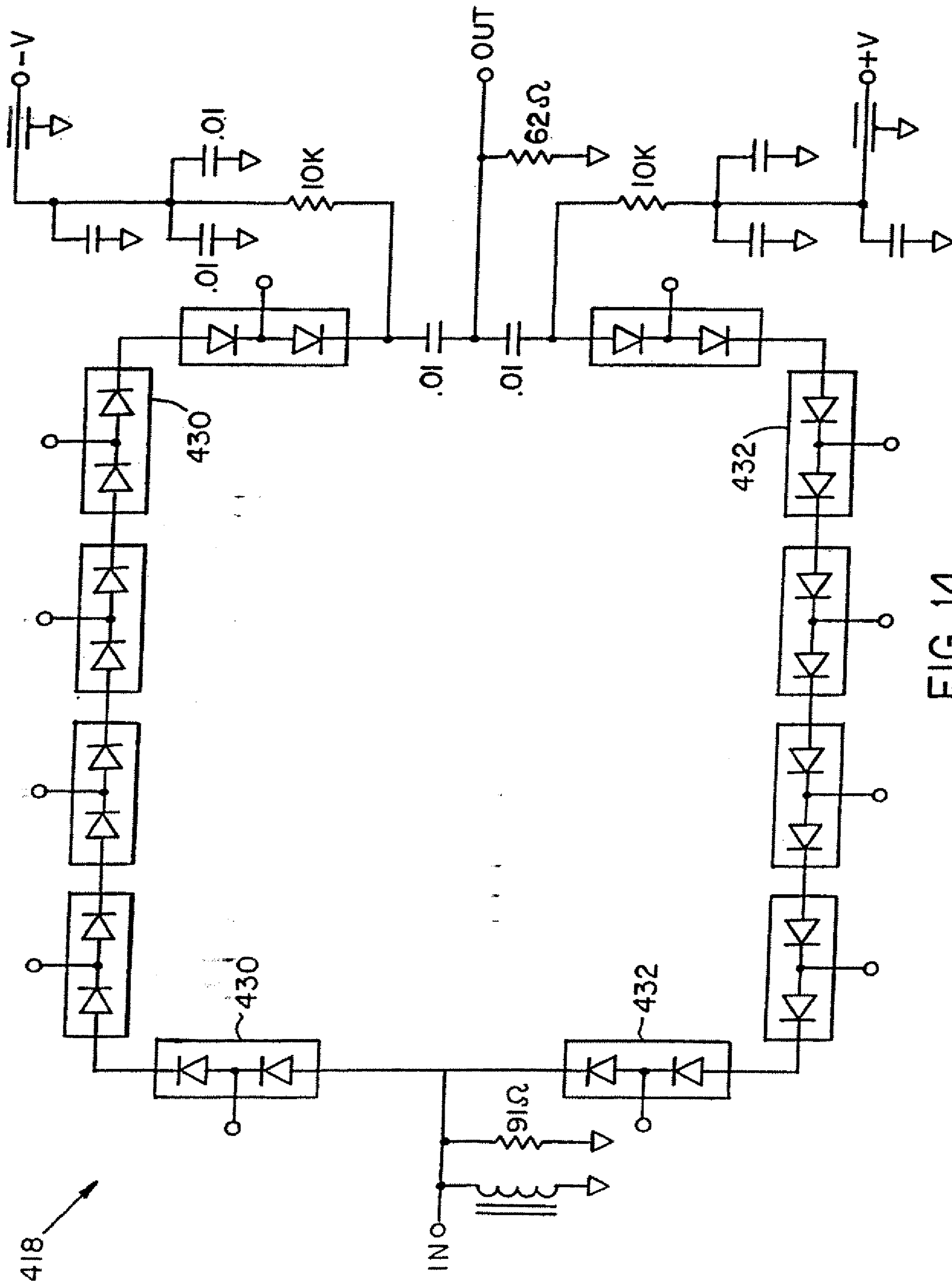


FIG. 14

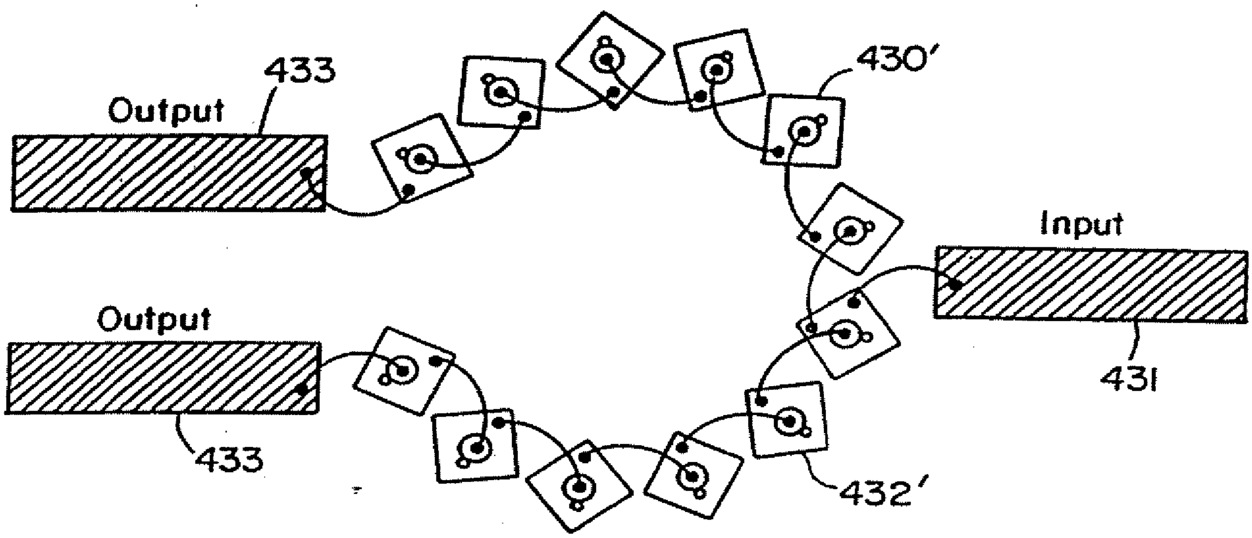


FIG. 15

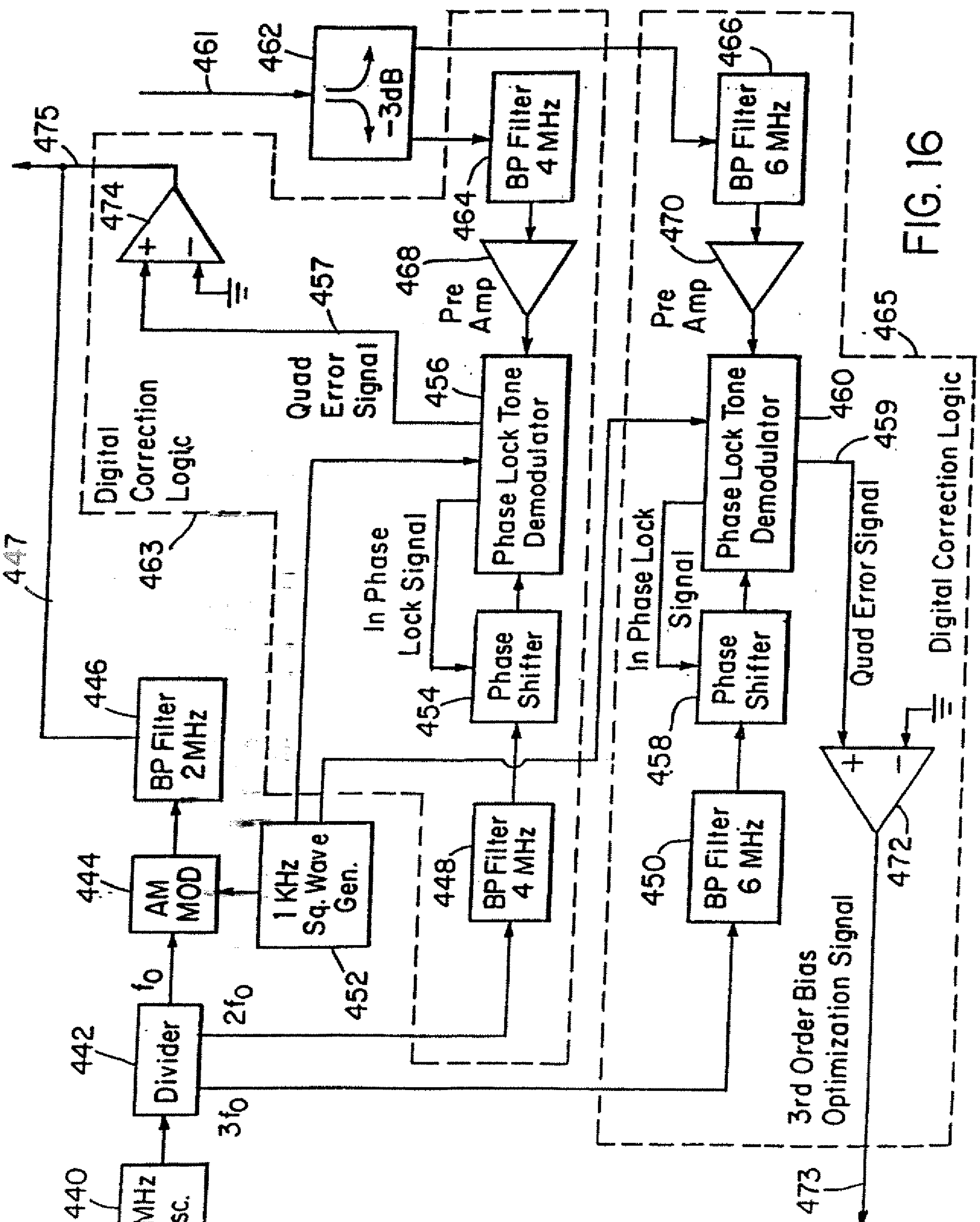

24 MHz Osc.
Divider
AM MOD
BP Filter 2MHz
1 KHz Sq. Wave Gen.
BP Filter 4 MHz
BP Filter 6 MHz
Phase Shifter
Phase Lock Tone Demodulator
Pre Amp
-3dB
Digital Correction Logic
Quad Error Signal
In Phase Lock Signal
3rd Order Bias Optimization Signal
f_o
$2f_o$
$3f_o$
440
442
444
446
447
448
450
452
454
456
457
458
459
460
461
462
463
464
465
466
468
470
472
473
474
475

FIG. 16

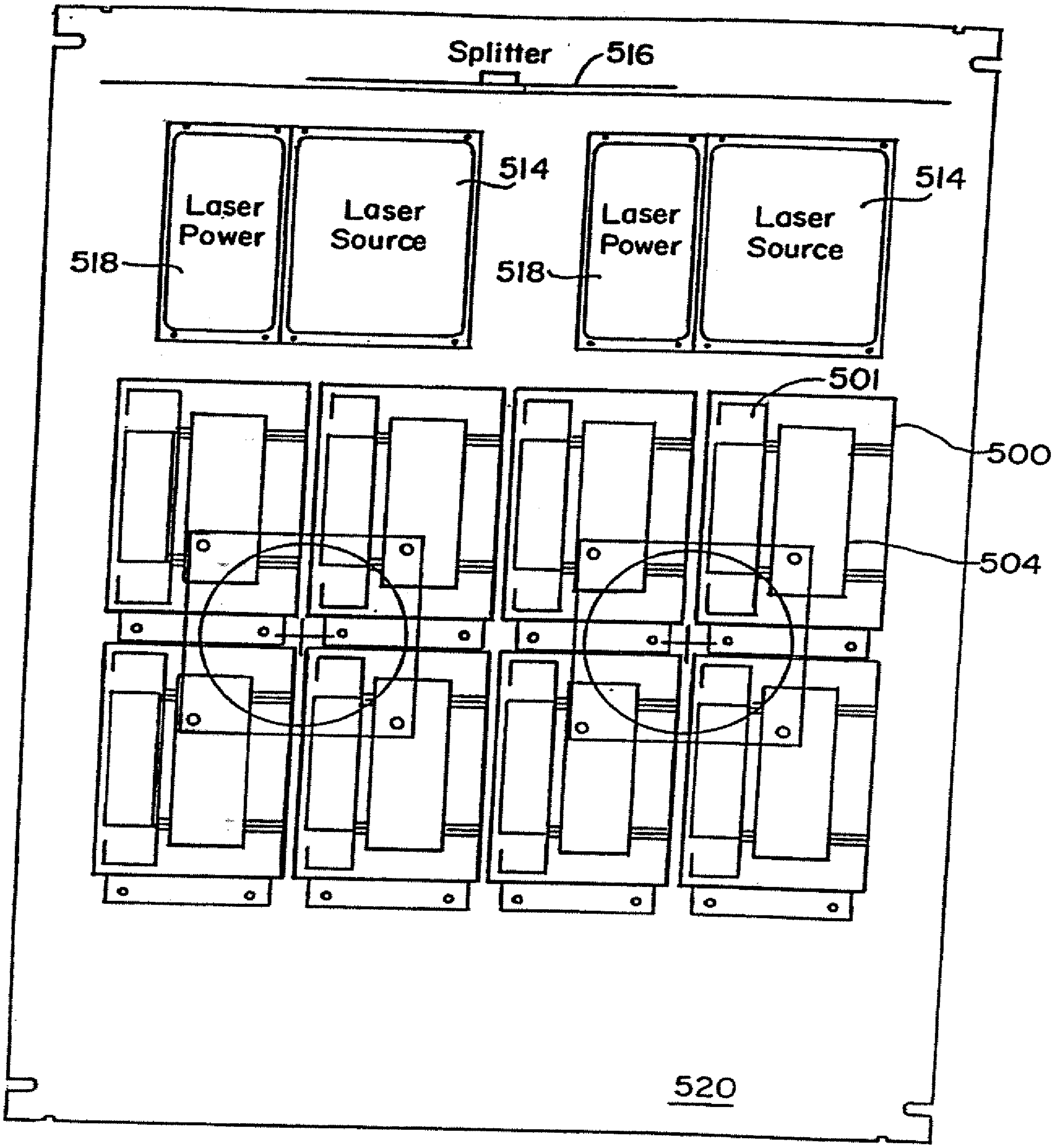

Splitter
516
Laser Power
Laser Source
514
518
Laser Power
Laser Source
514
518
501
500
504
520

FIG. 18

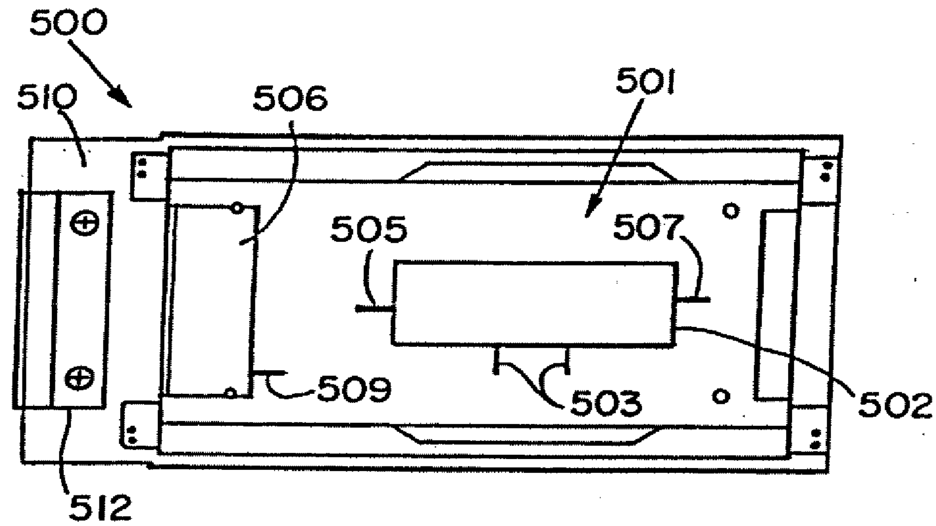


FIG. 17a

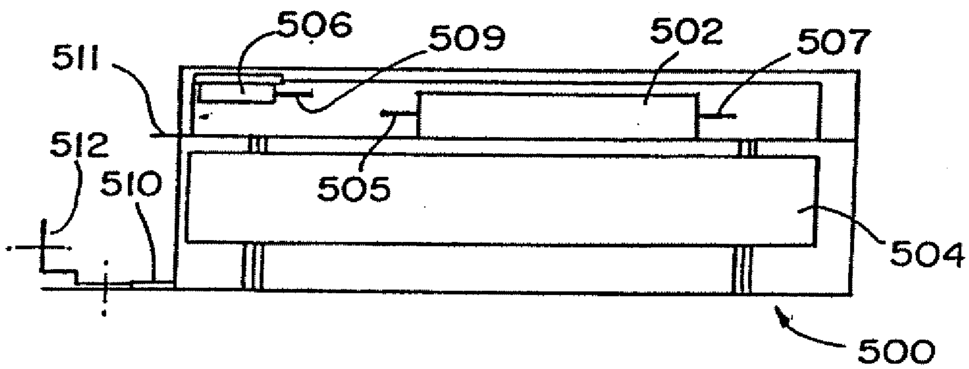


FIG. 17b

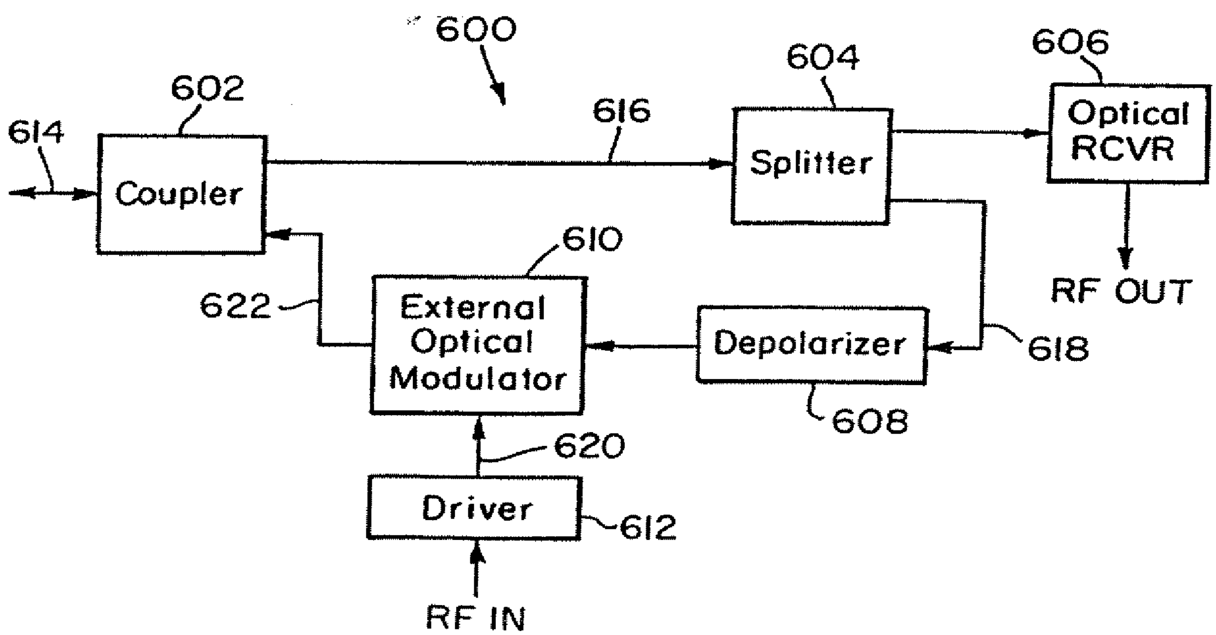


FIG. 19

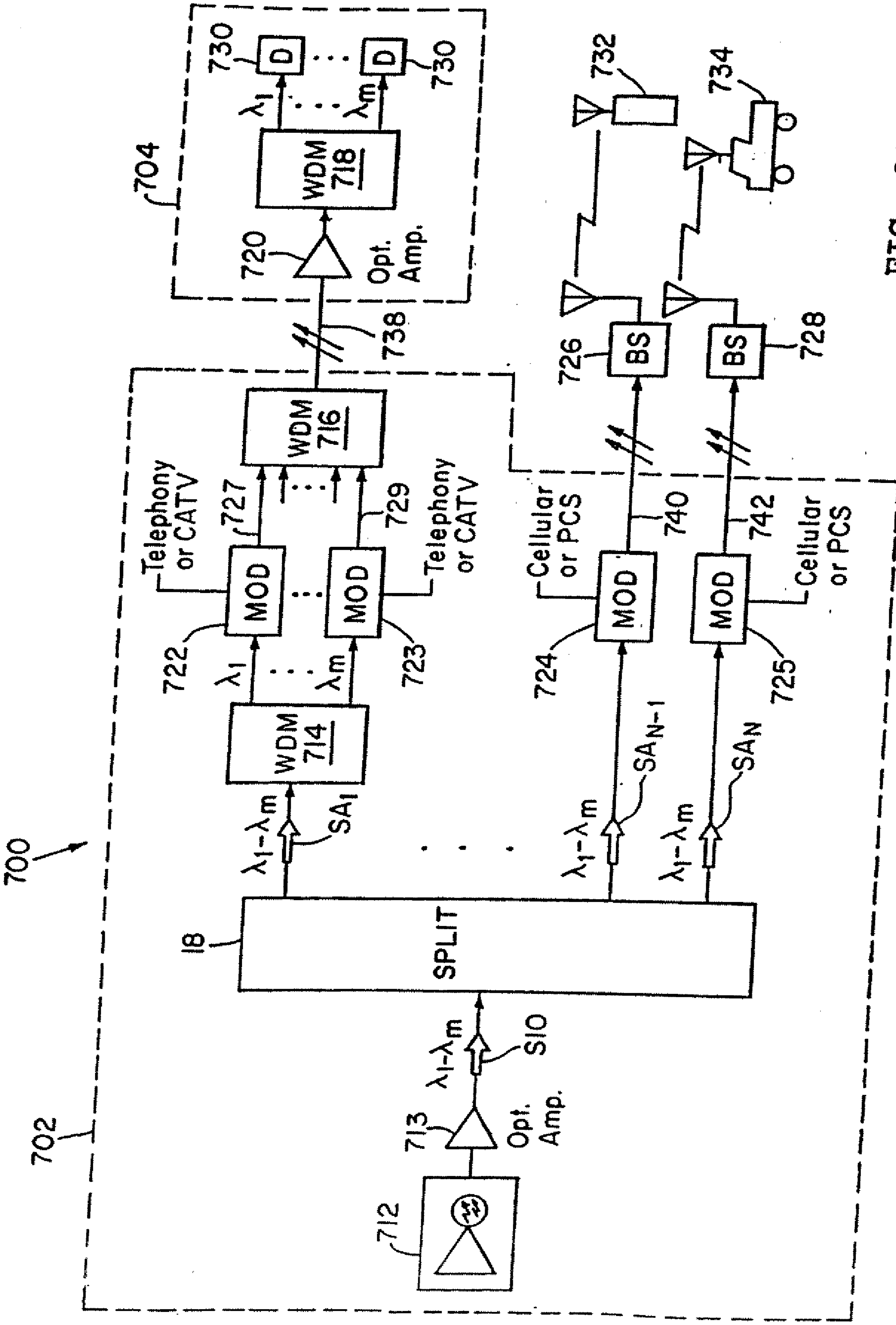

700
702
704
712
713
Opt. Amp.
λ_1-λ_m
SIO
18
SPLIT
SA1
SAN-1
SAN
WDM 714
WDM 716
WDM 718
MOD
722
723
724
725
727
729
Telephony or CATV
Cellular or PCS
740
742
738
720
730
D
BS
726
728
732
734

FIG. 20A

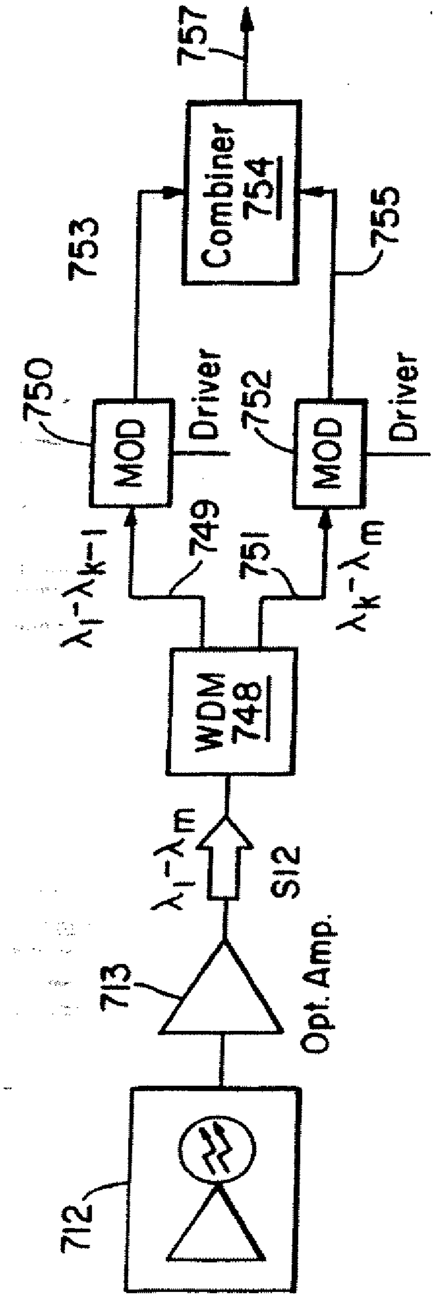

712
713
Opt. Amp.
λ1-λm
S12
WDM
748
λ1-λk-1
749
751
λk-λm
750
MOD
Driver
752
MOD
Driver
753
755
Combiner
754
757

FIG 20B

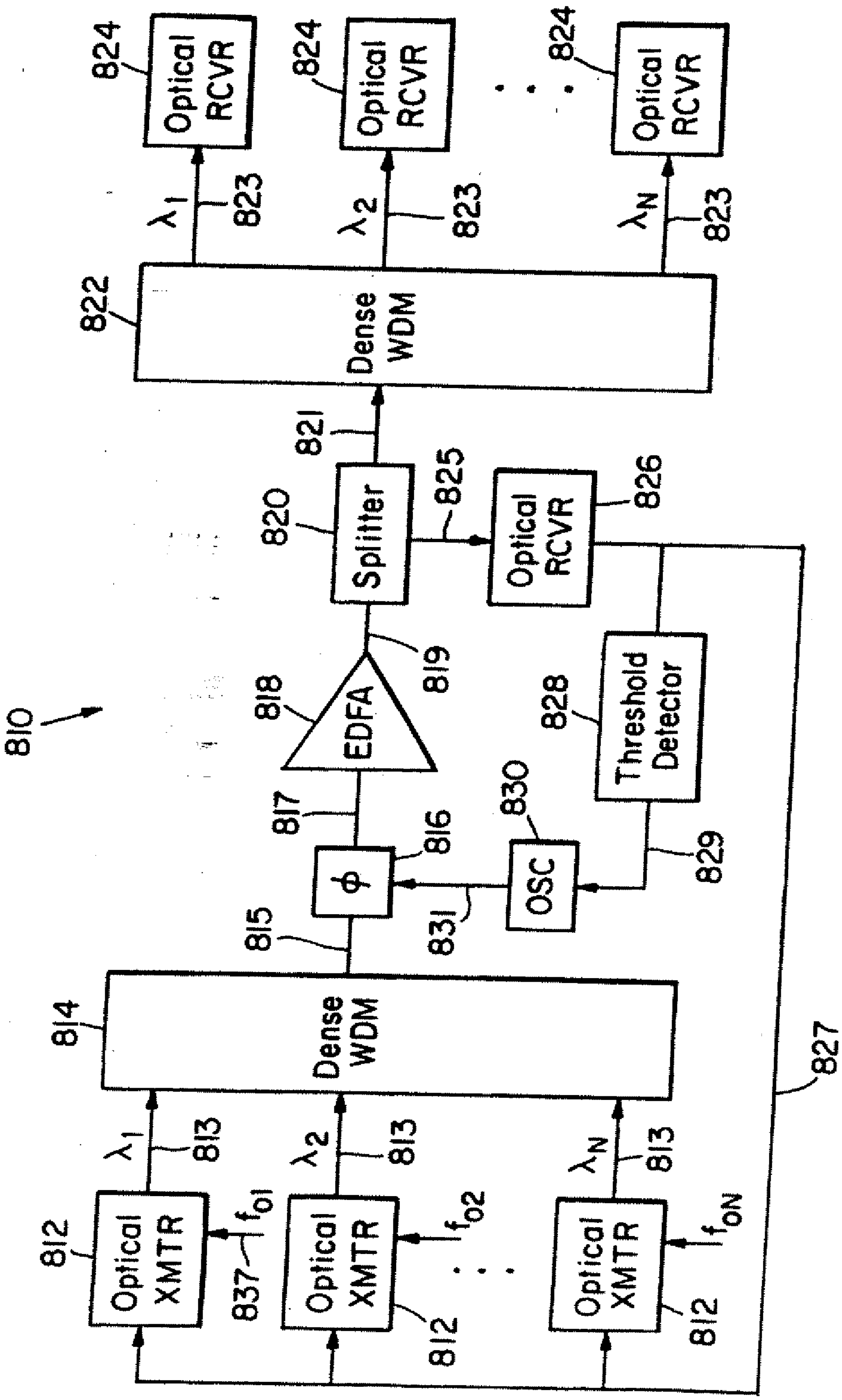

810
Optical XMTR
812
837
f_{01}
f_{02}
f_{0N}
λ_1
λ_2
λ_N
813
Dense WDM
814
815
ϕ
816
817
EDFA
818
819
Splitter
820
821
822
823
Optical RCVR
824
825
826
827
Threshold Detector
828
829
OSC
830
831

FIG. 21

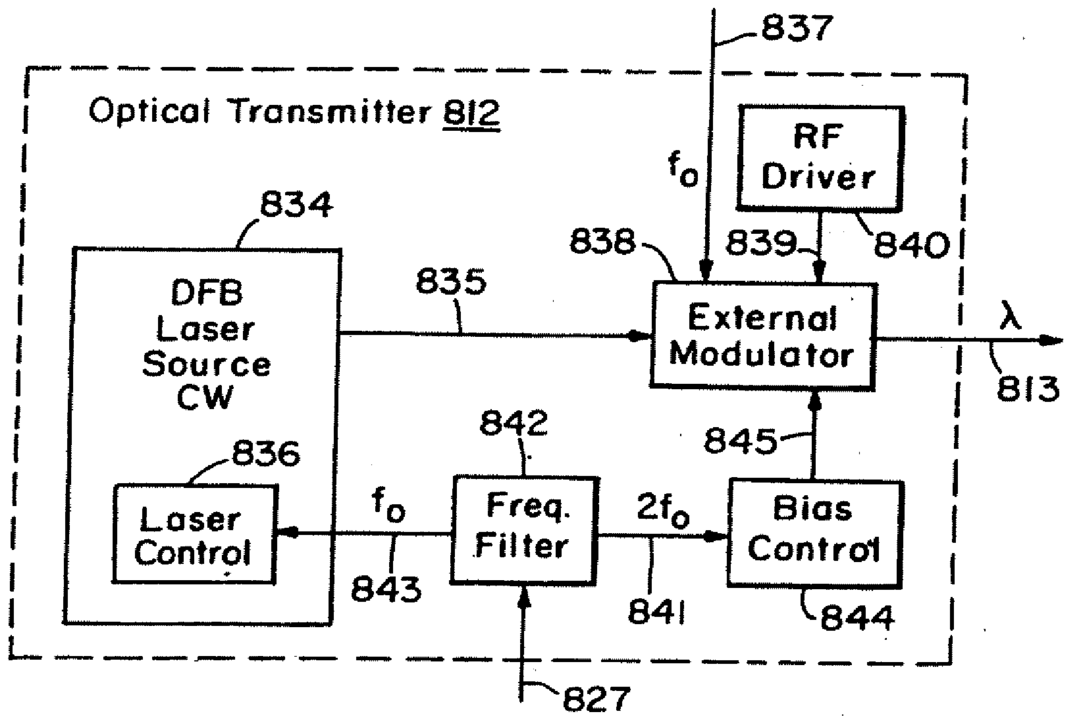

837
Optical Transmitter 812
f_o
RF Driver
834
838
839
840
DFB Laser Source CW
835
External Modulator
λ
813
842
845
836
Laser Control
f_o
Freq. Filter
$2f_o$
Bias Control
843
841
844
827

FIG. 22

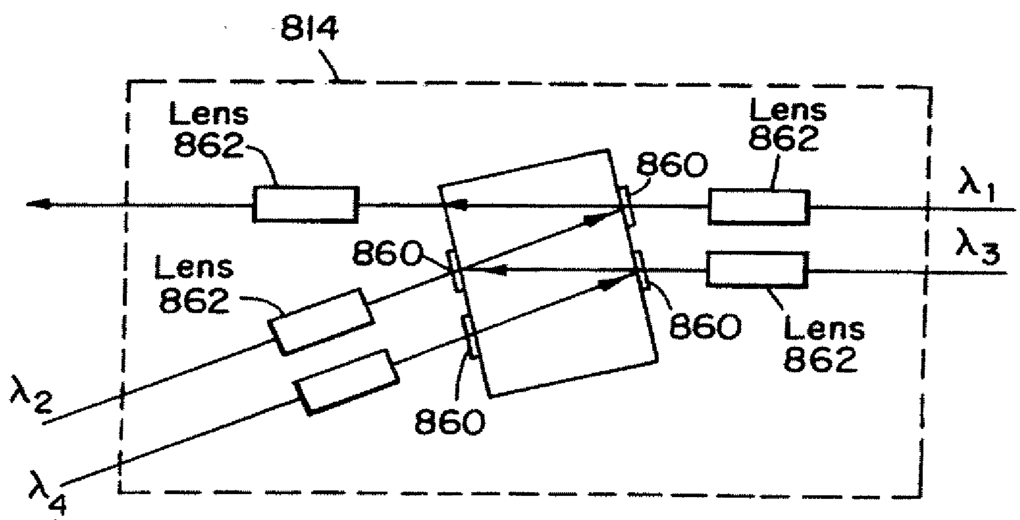

814
Lens 862
Lens 862
860
λ_1
860
λ_3
Lens 862
860
Lens 862
λ_2
860
λ_4

FIG. 23

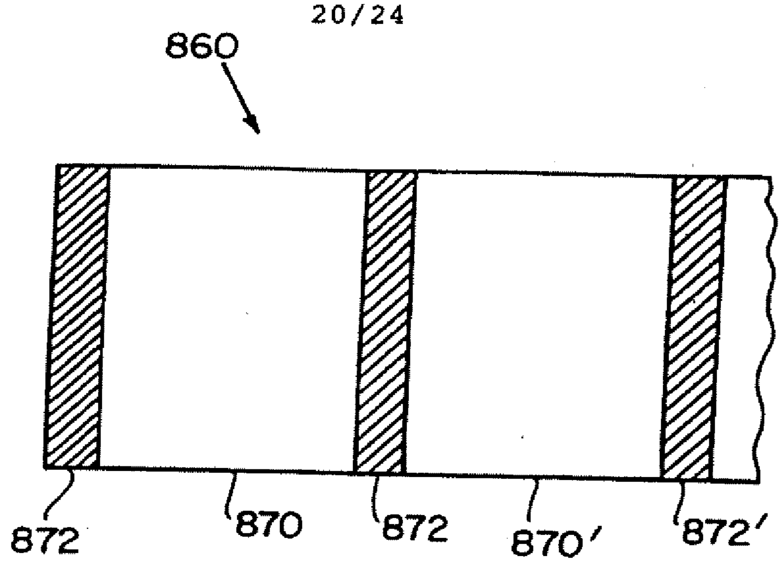

860
872
870
872
870′
872′

FIG. 24

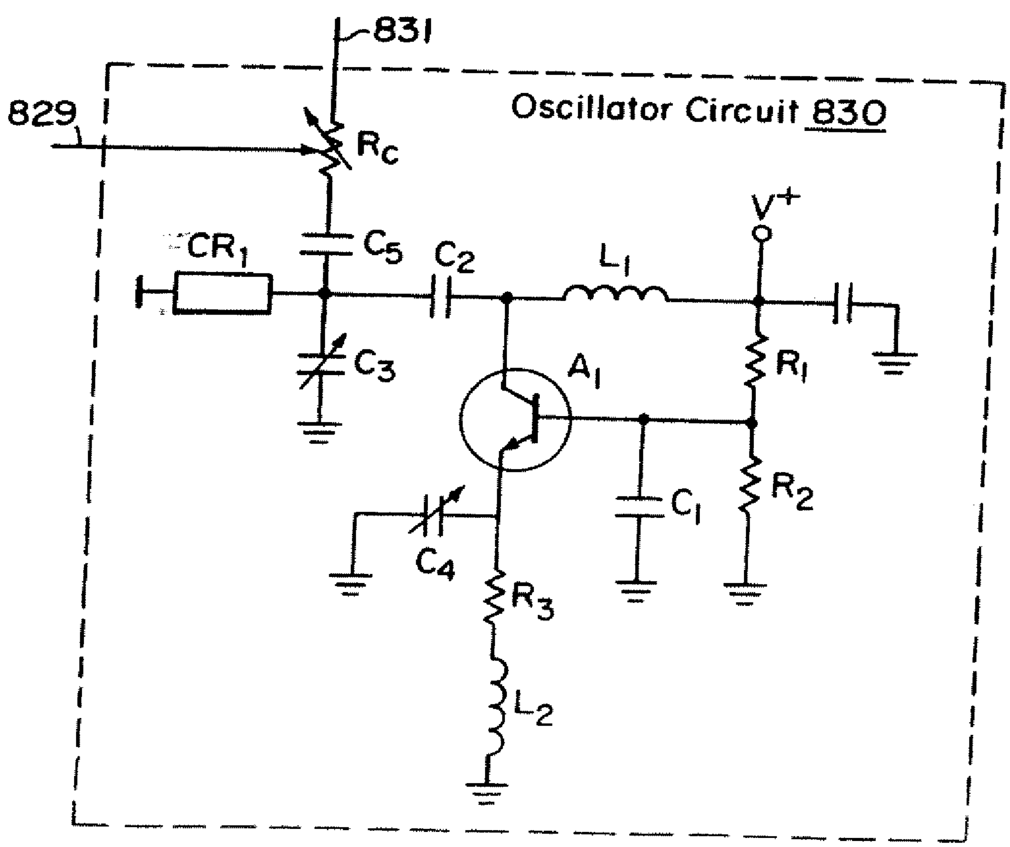

831
829
Oscillator Circuit 830
R_C
V^+
CR_1
C_5
C_2
L_1
C_3
A_1
R_1
R_2
C_1
C_4
R_3
L_2

FIG. 25

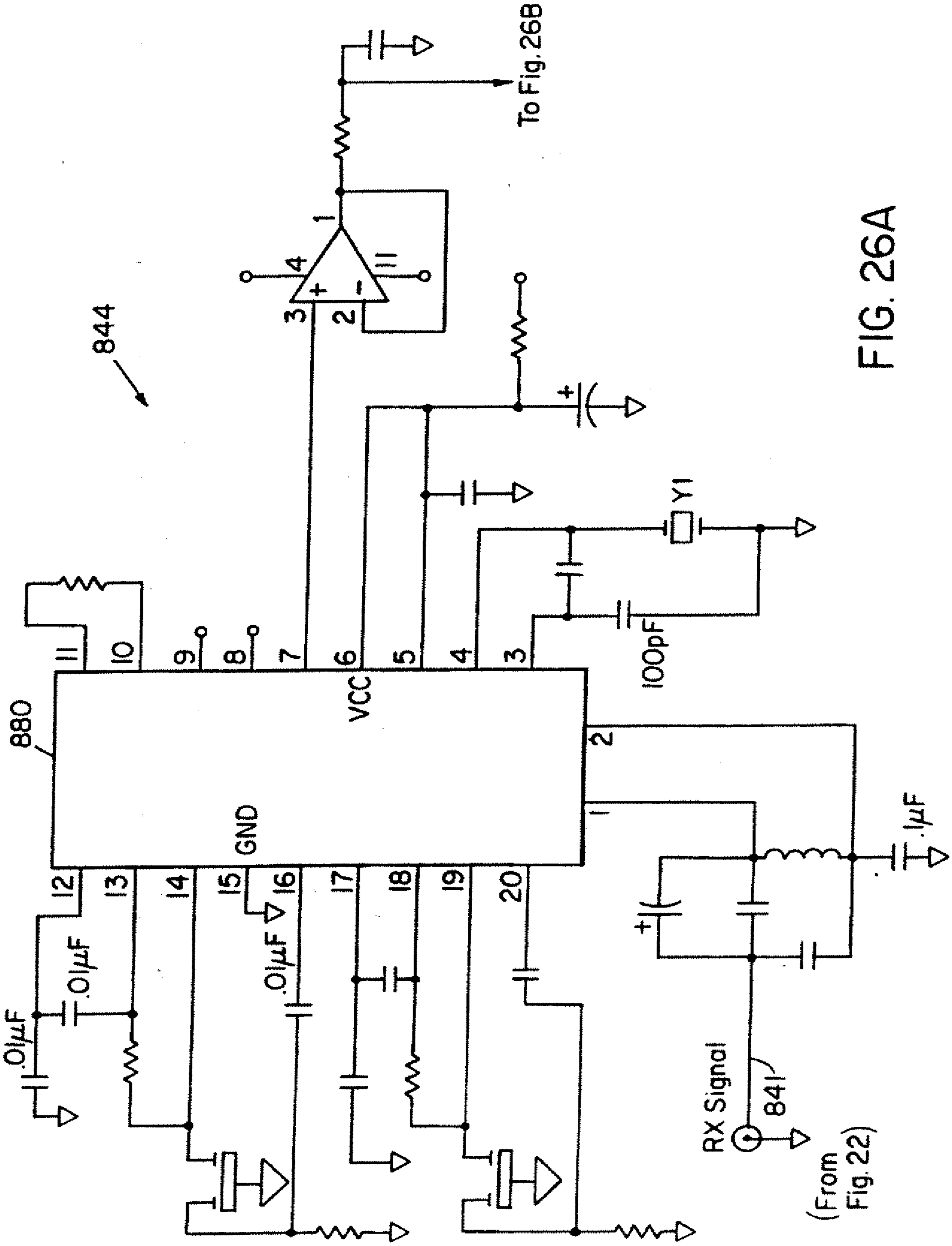

844
880
VCC
GND
To Fig. 26B
Y1
100pF
.1μF
.01μF
.01μF
.01μF
RX Signal
841
(From Fig. 22)

FIG. 26A

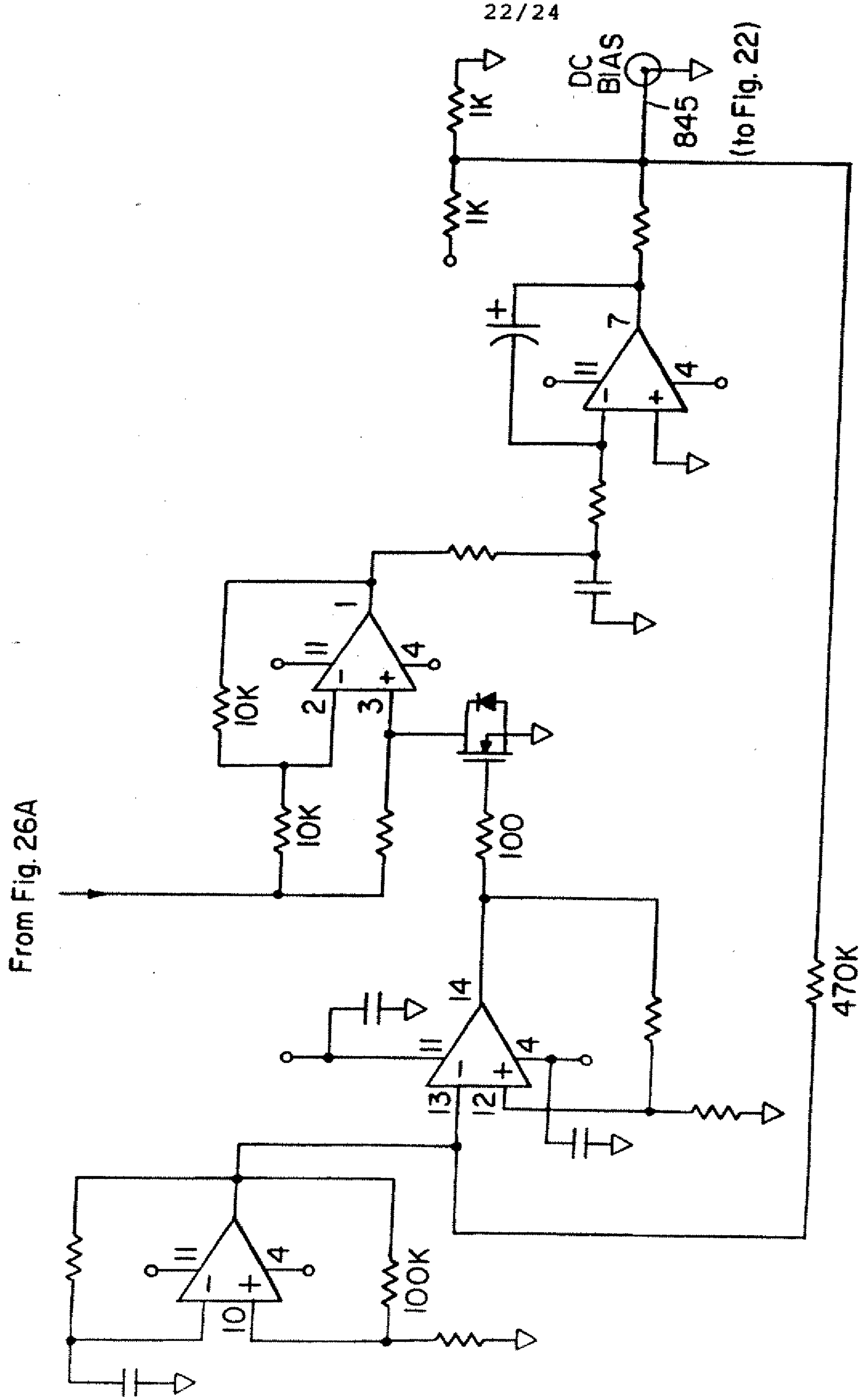


FIG. 26B

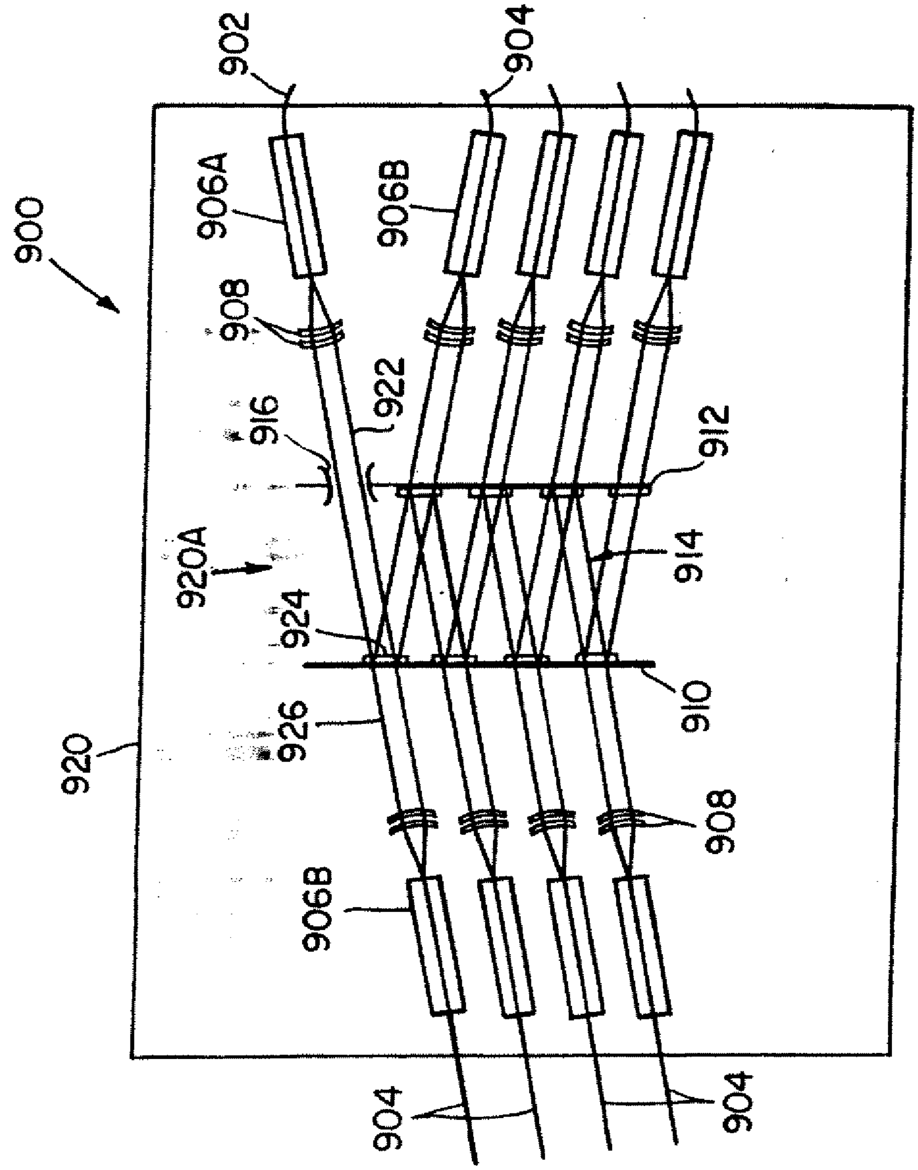

900
902
904
906A
906B
908
922
916
912
920A
914
924
910
926
920
906B
908
904
904

FIG. 27

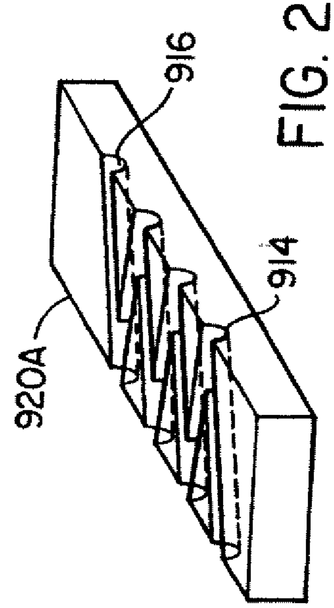


FIG. 28

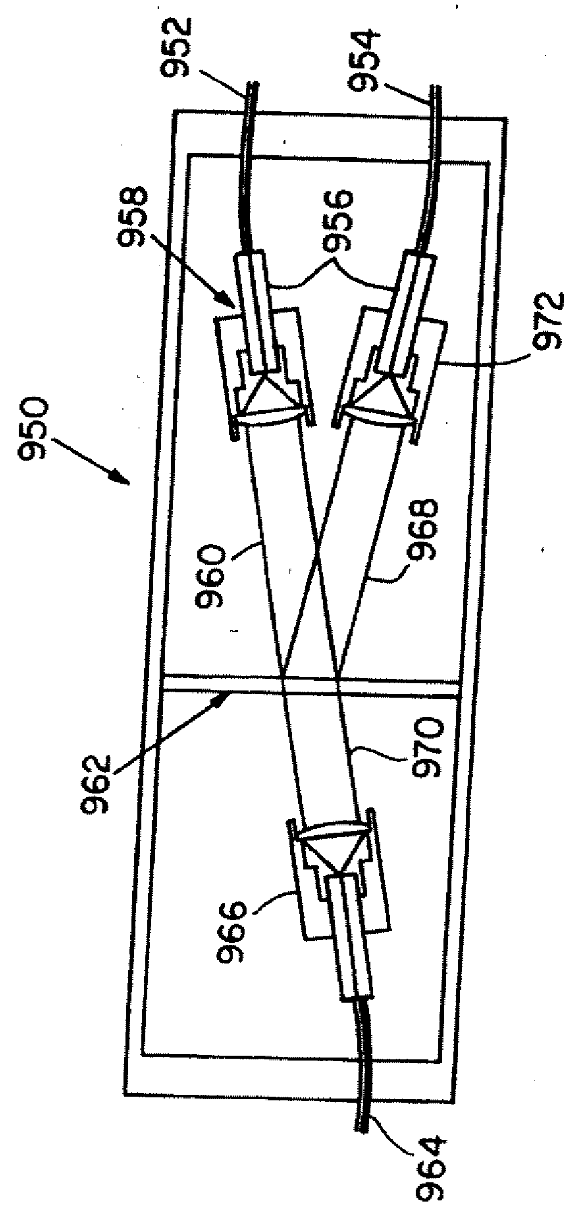


FIG. 29

INTERNATIONAL SEARCH REPORT

Inten al Application No
PCT/US 97/10923

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04N7/22 H04J14/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04N H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 242 802 A (NIPPON ELECTRIC CO) 28 October 1987 see column 2, line 1 - line 24	1,6,15,18
A	see column 3, line 1 - column 5, line 54; figures 1-7 ---	19
A	PATENT ABSTRACTS OF JAPAN vol. 004, no. 141 (E-028), 4 October 1980 & JP 55 093338 A (MATSUSHITA ELECTRIC IND CO LTD), 15 July 1980, see abstract ---	1-3,8,15,18,19
A	EP 0 475 331 A (CANON KK) 18 March 1992 see the whole document ---	1,2,4,15,18
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
13 October 1997	23. 10. 97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Fuchs, P

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INTERNATIONAL SEARCH REPORT

Inter. al Application No
PCT/US 97/10923

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 96 13104 A (BRITISH TELECOMM ;ELLIS ANDREW DAVID (GB)) 2 May 1996 see page 7, line 27 - page 8, line 23; figure 1 see page 10, line 9 - page 12, line 2; figure 7 ---	1,2,7, 15,18
A	US 5 107 360 A (HUBER DAVID R) 21 April 1992 see the whole document -----	1,15,18

1

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inten   al Application No
PCT/US 97/10923

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		CA 1279413 A	22-01-91
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		EP 0787390 A	06-08-97
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